CORRECTIVE MEASURES STUDY
WORK PLAN
NAVAL SUPPORT ACTIVITY MID-SOUTH
AOC A – NORTHSIDE FLUVIAL GROUNDWATER
MILLINGTON, TENNESSEE

Revision: 3

Comprehensive Long-Term Environmental Action Navy (CLEAN)
Contract Number: N62467-89-D-0318
CTO-094

Prepared for:

Department of the Navy
Southern Division
Naval Facilities Engineering Command
North Charleston, South Carolina

Prepared by:

EnSafe Inc.
5724 Summer Trees Drive
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April 13, 2000

ENSAFE

ENSAFE INC. ENVIRONMENTAL AND MANAGEMENT CONSULTANTS

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April 13, 2000

Commanding Officer
Attn: James Reed/18812JR
SOUTHNAVFACENGCOM
2155 Eagle Drive
P.O. Box 190010
North Charleston, SC 29419-9010

Subject: CTO-094; NSA Mid-South RCRA Facility Investigation, Millington, Tennessee

Document Transmittal - *Corrective Measures Study Work Plan, AOC A — Northside Fluvial Groundwater, Revision 3*, April 13, 2000

Reference: Contract N62467-89-D-0318 (CLEAN II)

Dear Sir:

This letter is provided to document submittal of the NSA Mid-South *Corrective Measures Study Work Plan. AOC A — Northside Fluvial Groundwater, Revision 3.* The document has been distributed as shown on the attached NSA Mid-South RFI Distribution List.

If you have any questions or comments of a technical nature, please contact me at 901/372-7962. Comments or questions of a contractual nature should be directed to Debra Blagg at 901/386-9344.

Sincerely,

EnSafe Inc.

By: John Stedman, Jr.

Enclosures: As Stated

cc: Contracts File: CTO-094 (w/out enclosure)
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Response to Comments
Corrective Measures Study Work Plan (Revision 02)
AOC A — Northside Fluvial Groundwater
Naval Support Activity Mid-South
Millington, Tennessee

USEPA Comments:

Comment 1:
Page 3-1, Section 3.0, 3rd sentence — I believe some SWMUs which will be addressed by this work plan were not included such as SWMU 18 and N-12. All SWMUs included in the AOC A should be listed.

Response:
SWMU 18 has been added to the work plan. Site N-12 will be addressed in the Northside Loess groundwater CMS work plan since the contamination was detected in shallow groundwater. A list of all the SWMUs in the AOC A has been added to Section 3.1.

Comment 2:
Page 3-4, 2nd paragraph, last sentence — States "Geophysical logs from municipal supply wells indicate the Cook Mountain Formation ranges in thickness from 0 to 60 feet." I believe the thickness ranges from 10 to 60 feet.

Response:
Yes, the thickness is from 10 to 60 feet and the last sentence has been changed.

Comment 3:
Section 3.3 — This section should be updated to include the groundwater sampling results since October 1998.

Response:
Section 3.3 has been updated to include groundwater sampling through July 1999 as referenced in the AOC A RFI (Revision 2) and the AOC A RFI Addendum.

Comment 4:
Page 3-19, 3rd sentence — Since groundwater contamination has been detected at the facility boundary this sentence should be revised.

Response:
This sentence and figure have been removed.

Comment 5:
Page 3-22, 1st bullet — See previous comment.

Response:
This bullet has been taken out and replaced with updated information documenting the contamination detected at the boundary.

Comment 6:
Page 4-4, last sentence — The words "will be prepared" should be removed from this sentence.

Response:
This change has been made.

Comment 7:
Need to ensure this section for evaluating natural attenuation follows EPA's guidance. EPA's guidance on evaluating natural attenuation can be found at http://www.epa.gov.ada.reports.html.

Response:
A sentence has been added at the end of the natural attenuation section which states, "In addition to the above, other applicable elements of EPA's *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater* will be used to evaluate natural attenuation (USEPA, 1998).

Comment 8:
Page 4-9, Advection — "effectively porosity" should be changed to "effective porosity."

Response:
This change has been made.

Comment 9:
Page 4-10, 1st paragraph — Since it appears that we are scrapping the MYGRT model this section should be changed. We may want to wait to make this change until we have our meeting in April when we discuss modeling.

Response:
In the April meeting, the model MYGRT was replaced with BIOCHLOR. Therefore, the 1st paragraph has been changed.

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Abbreviations and Acronyms

AOC	Area of Concern
ASTM	American Society for Testing and Materials
BCT	BRAC Cleanup Team
BRAC	Base Closure and Realignment Act
CMI	Corrective Measures Implementation
CMS	Corrective Measures Study
COPC	chemicals of potential concern
CRP	Community Relations Plan
CSI	Confirmatory Sampling Investigation
DNAPL	dense-non-aqueous phase liquid
DPT	direct push technology
DQO	data quality objectives
EDGe	Engineering, Design, and Geosciences Corp. Inc.
EIC	engineer-in-charge
HSWA	Hazardous and Solid Waste Amendments
IR	Installation Restoration (Program)
MCLs	maximum contaminant levels
NPDES	National Pollutant Discharge Elimination System
NSA	Naval Support Activity
P&T	pump and treat
PAHs	polyaromatic hydrocarbons
POC	point of compliance
POTW	publicly owned treatment works
PRGs	preliminary remedial goals
RAB	Restoration Advisory Board
RBCs	risk-based concentrations
RFA/RFI	RCRA Facility Assessment/RCRA Facility Investigation
RGO	remedial goal option
SSL	soil screening level
SWMU	Solid Waste Management Unit
TDEC	Tennessee Department of Environment and Conservation
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UV-OX	ultraviolet oxidation
VOCs	volatile organic compounds

1.0 INTRODUCTION

As a result of the Base Closure and Realignment Act (BRAC) of 1990, a portion of Naval Support Activity (NSA) Mid-South has been closed and is being transferred to the City of Millington. To expedite this transfer, the BRAC Cleanup Team (BCT) decided to designate groundwater in the fluvial deposits aquifer beneath the entire NSA Mid-South Northside as Area of Concern (AOC) A and perform a single Corrective Measures Study (CMS) rather than performing individual CMSs for each Solid Waste Management Unit (SWMU) on the Northside in which fluvial groundwater contamination has been identified. Figure 1-1, a topographic map of NSA Mid-South and the surrounding area, shows the Northside and Southside base boundaries.

The CMS is part of the Resource Conservation and Recovery Act (RCRA) Corrective Action Program which follows the RCRA Facility Assessment/RCRA Facility Investigation (RFA/RFI) process. Corrective Measures Implementation (CMI) follows the CMS. The ultimate goal of a CMS is to select corrective measures alternatives which mitigate threats to public health, welfare, and the environment and provides continuing protection to them. CMSs entail development, screening, and evaluation of alternative remedial options. CMS objectives are to develop and evaluate alternatives with respect to protection of public health and environment, compliance with applicable requirements (e.g., maximum contaminant levels), and to reduce contaminant mobility and/or toxicity.

This plan addresses the general procedures to be followed during the CMS for NSA Mid-South Northside fluvial deposits groundwater. Discussions of overall corrective measures technology identification, screening, and evaluation are included in this plan.

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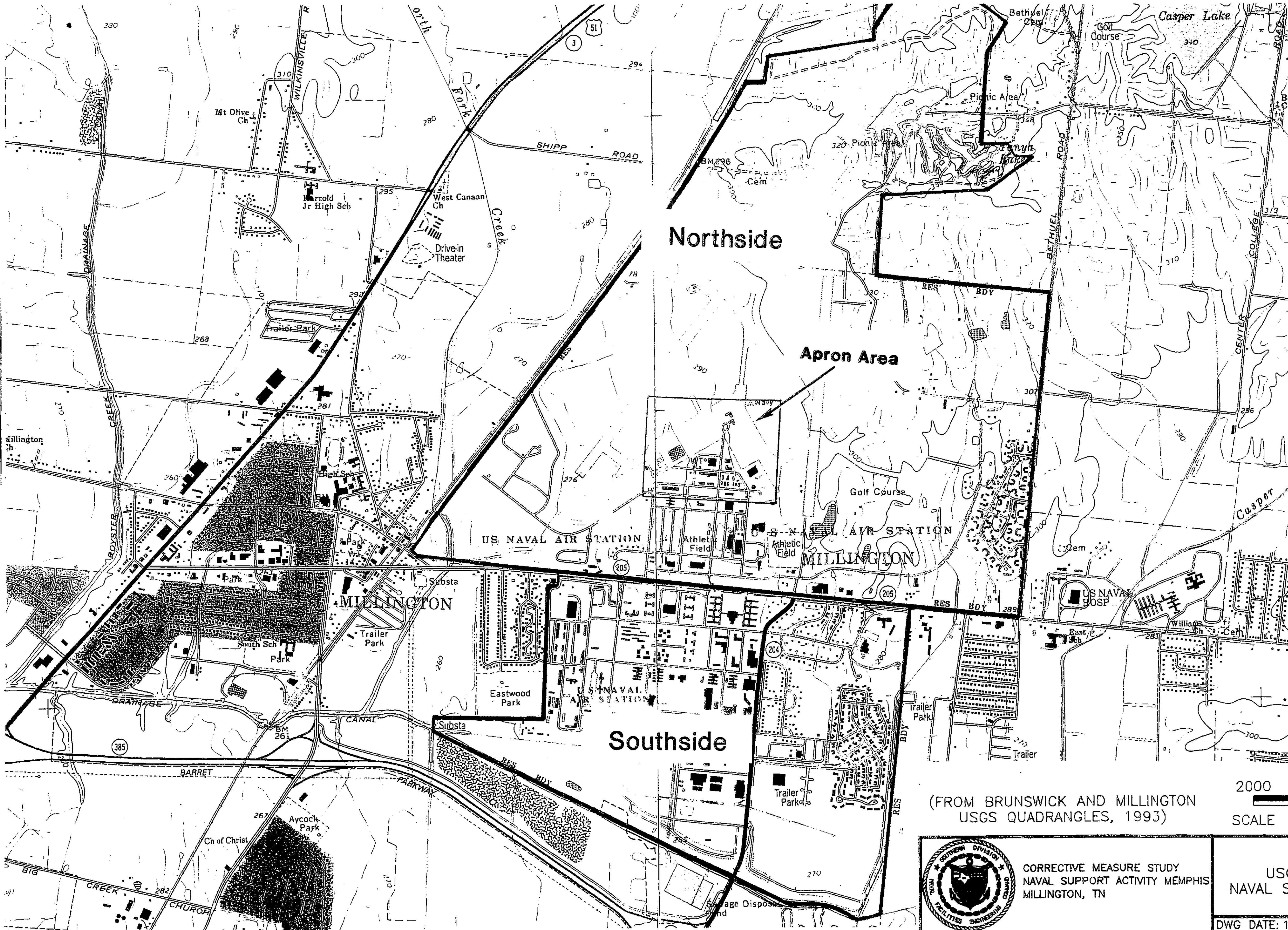

(FROM BRUNSWICK AND MILLINGTON USGS QUADRANGLES, 1993)

2000 0 2000

SCALE FEET

CORRECTIVE MEASURE STUDY
NAVAL SUPPORT ACTIVITY MEMPHIS
MILLINGTON, TN

FIGURE 1-1
USGS TOPOGRAPHIC MAP
NAVAL SUPPORT ACTIVITY MEMPHIS

DWG DATE: 10/22/97 | DWG NAME: BOARD

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This plan has been prepared for NSA Mid-South as part of the Department of Defense Installation Restoration (IR) Program and is intended to satisfy Condition IV G-1(a)(b) of the Hazardous Waste Management permit (TNHW-094) and also the Hazardous and Solid Waste Amendments (HSWA) permit (HSWA-TN 002) issued to NSA Mid-South by the Tennessee Department of Environment and Conservation (TDEC) and the U.S. Environmental Protection Agency (USEPA) Region IV, respectively. These permits combine to make the complete RCRA permit for NSA Mid-South.

1.1 Purpose of CMS

The CMS is intended to identify and evaluate potential remedial alternatives for a given site or a group of sites identified through the RFI or other investigations as needing further evaluation. Although not required, the permittee may choose to evaluate several corrective measures technologies. Because of the complexity of the environmental impacts at this AOC, the BCT has determined that several corrective measure technologies should be evaluated.

Evaluation of viable remedial options will be based primarily upon their ability to adequately protect human health and the environment, while complying with all applicable regulatory concerns and standards. To achieve this objective, the CMS will consider the following criteria during the evaluation process:

Primary Criteria

- Protection of Human Health and the Environment
- Attainment of Media Cleanup Standards
- Source Control
- Compliance with Applicable Standards for Managing Wastes

Secondary Criteria

- Long-Term Reliability and Effectiveness
- Reduction of the Toxicity, Mobility, or Volume of Wastes
- Short-Term Effectiveness
- Implementability
- Cost

These criteria, as well as the process used to identify, develop, and evaluate potential remedial alternatives, will be discussed in this plan.

1.2 RCRA Permit Issues

RFI activities at NSA Mid-South are currently regulated through the RCRA permit issued by TDEC and USEPA. The Hazardous Waste Management permit was reissued by TDEC on September 24, 1996, and will expire September 24, 2006. The original HSWA permit of September 15, 1986 was reissued by USEPA Region IV on April 1, 1998.

The HSWA portion of the permit required NSA Mid-South to conduct an RFA to identify and characterize all active and inactive SWMUs. The Navy retained Engineering, Design, and Geosciences Group, Inc. (EDGe) in December 1986 to conduct the RFA and perform an RFI to evaluate SWMUs known, suspected, or presumed to have releases of hazardous constituents. EDGe prepared the Draft RFA and RFI reports concurrently and submitted them in April 1987. The reports identified 58 potential SWMUs and recommended 34 for additional study. Since 1987, eight more sites have been added and a formerly identified site has been divided into two sites, bringing the total number of SWMUs to 67. On September 24, 1996, TDEC reissued the Hazardous Waste Management permit with modifications to add the new SWMUs and one AOC, the Northside fluvial deposits groundwater. Thus, there are currently 67 SWMUs and one AOC listed in the permit modification.

The RCRA Part B Permit for NSA Mid-South specifies that TDEC and USEPA will review RFI documents and notify NSA Mid-South if further investigations, CMSs, or corrective actions are needed. It is anticipated that a permit modification will be required at the end of the CMS when the program progresses from the CMS to the CMI stage. The CMS is expected to present the general methodology for transition to CMI. The CMS will also focus on the remedial timeframe, permitting, and regulatory concerns for each alternative.

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2.0 GENERAL APPROACH TO CMS

The following discusses general approaches to be used during the CMS process for data collection, identifying target media cleanup goals, statistical applications to corrective measures evaluation, modeling, and cost estimating. These approaches are fundamental to a CMS.

2.1 Data Evaluation

Defining the nature of potential contaminants or chemicals of potential concern (COPC) was the initial step in the RFI data-collection process, which depends largely on the quality (as defined by data quality objectives [DQO]). A minimal number of biased samples were collected following DQO definitive data (formerly Levels III and IV) protocols and procedures. Quality criteria are outlined in the *Comprehensive RFI Work Plan — Naval Air Station Memphis* (E/A&H, 1994). In addition to establishing initial concentration measures for COPCs, the data will be used in the CMS process to define preliminary remedial goals (PRGs) and to evaluate corrective measures technologies. Additional data may be necessary to fill data gaps; define quantities, volume, and mass; or to evaluate the effectiveness or feasibility of a technology. If additional data are required, an addendum to this plan describing procedures for collecting and analyzing these data will be prepared and submitted to the BCT.

DQO Process

Data quantity and quality can have a direct effect on choosing the correct remedial option. However, a point is reached beyond which more and/or better data do not significantly increase the probability of making the right choice. The DQO process is a systematic way of evaluating the data's impact on decision-making, and determining the degree of uncertainty associated with such decisions.

DQOs will be established during the CMS to properly evaluate and compare the various remedial technologies and alternatives. A detailed description of the DQOs will be provided in the CMS report. The overall objective of the CMS — *to select corrective measures alternatives which mitigate threats and protect public health, welfare, and the environment* — will be maintained while establishing DQOs for individual processes or problems within remedial technologies and alternatives.

Typically, the following broad steps will be adopted in establishing and describing the DQO process:

- State the nature of the problem.
- Identify the decision.
- Identify decision-making input.
- Define the study boundaries.
- Develop a decision rule.
- List the limitations on decisions and associated errors.
- Optimize the decision for obtaining the data.
- Apply the data to the quantification and qualification process of the particular problem.
- Assess the quality of the data, i.e., evaluate the data set to determine whether data are sufficient for decision-making.

The DQO process will be applied to the following tasks, alternatives, processes, or problems:

- Statistical analyses and tests to be performed on the contaminant concentration data.

- Geochemical parameter analysis and preliminary screening for evidence of biodegradation at the site as part of the natural attenuation remedy evaluation.

- Input parameters to be used in the fate and transport model for natural attenuation; the assumptions and limitations of the model; the quantitative effect of numerical values attached to each input parameter such as groundwater velocity, dispersion, and adsorption; and how the sensitivity analysis for the fate and transport model fits into the DQO process.

- Input parameters for models and calculations for evaluating the pump and treat remedy alternative; input parameters to be used for other applicable remedial alternatives.

- Computation of the costs and remediation time of each alternative; the assumptions, limitations, and uncertainties associated with these determinations.

- Planning for long-term groundwater monitoring and analysis of long-term monitoring data; development of effectiveness evaluation of the chosen remedy.

2.2 Development of Target Media Cleanup Goals

PRGs or site-specific goals for corrective measures are based on human health and environment criteria, information gathered during the RFI, USEPA guidance, and applicable federal and state statutes. PRGs are typically based on promulgated standards such as maximum contaminant levels (MCLs) and surface-water-quality criteria; and relevant nonpromulgated requirements such as EPA's risk-based concentrations (RBC) and EPA's soil-screening levels (SSL). Human health and ecological risk-based concentrations, estimated in accordance with USEPA risk-assessment guidance, may also be considered when establishing PRGs. The USEPA guidance document

RCRA Corrective Action Plan (USEPA, 1994) outlines issues to be considered in developing corrective action objectives for groundwater, soil, surface water, sediment, and air.

Risk Assessment

Chemical concentrations present in the Northside fluvial deposits groundwater exceed MCLs and were determined by the BCT to pose a risk, thereby warranting a CMS. Presently, TDEC considers all groundwater to be potential drinking water and, as such, should have contaminant concentrations reduced to less than MCLs, although it is unlikely groundwater in the fluvial deposits at NSA Mid-South will be used as a drinking water source. The BCT decided not to perform a risk assessment for the Northside fluvial deposits groundwater during the RFI because promulgated groundwater standards (MCLs) have been exceeded.

2.3 Points of Compliance

As part of the CMS, points of compliance (POC) will be evaluated. For groundwater compliance, the USEPA Region IV Memorandum on Media Cleanup Standards and Conditional Remedies in the HSWA Program (USEPA, 1996) details several alternatives for the POC wells that were outlined in proposed Subpart S, including the physical edge of the SWMU, throughout the plume, the leading edge of the plume, if contained within the property, or the facility boundary. USEPA Region IV recommends that the POC be set at the physical edge of the SWMU for final remedies. As will be discussed in the following section, there are numerous plumes within AOC A, adding a degree of complexity to determining the points of compliance.

2.4 Modeling

This section primarily discusses groundwater flow models, although the modeling process and many of the general comments apply to other types of environmental models.

The following American Society for Testing and Materials (ASTM) standards have been established for groundwater modeling, and will be followed when applicable:

- D 5447-93: Application of a Ground-Water Flow Model to a Site-Specific Problem
- D 5490-93: Comparing Ground-Water Flow Model Simulations to Site-Specific Information
- D 5609-94: Defining Boundary Conditions in Ground-Water Flow Modeling
- D 5611-94: Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application

A copy of each of these standards is included in Appendix A.

Description of the Models

Environmental models are typically either numerical or analytical. Generally, numerical models can be used for more complex simulations, and can incorporate heterogeneities, varying physical and chemical conditions over the site, and differing boundary conditions. Analytical models are simpler calculations for homogenous site conditions. Simulations using numerical models generally take much longer than those using analytical models, and are therefore much more expensive.

2.5 Cost Estimating

There are several approaches to cost estimating. This section presents the approach to be used when evaluating cost of corrective measure technologies. Cost estimates will include both capital and operation and maintenance (O&M) costs. Capital cost will include cost for engineering, site preparation, construction, materials, labors, sampling/analysis, waste management and disposal, permitting, and health and safety measures. Likewise, O&M costs will include labor, training, sampling/analysis, maintenance materials, utilities, and waste disposal and/or treatment.

Costing Sources

- *Means Environmental Remediation Cost Data-Assemblies* (R.S. Means Company, 1998)
- *Means Environmental Remediation Cost Data-Unit Price* (R.S. Means Company, 1998)
- Industry Quotes

Costs will be evaluated to a present worth value by using a combination of *USEPA's Remedial Action Costing Procedures* (EPA/600/8-87/049, October 1987), *USEPA's Superfund Cashout User's Manual* (PB94-141678, September 1992), and *Engineering Economic Analysis* (1988) by Donald G. Newman. A present worth analysis makes it possible to compare remedial alternatives on the basis of a single cost representing an amount that, if invested in the base year and disbursed as needed, would be sufficient to cover all costs associated with the remedial action over its planned life. Therefore, for cost comparison only, it is advantageous to seek the remedial alternative with the lowest present worth. An inflation rate of 1.22%, based on the Chemical Engineering Plant cost index for years 1989 through 1995 and a prime interest rate of 8.25%, are assumed for base calculations. The present worth cost will be estimated from midyear and an increase in the discount rate would decrease the present worth of the alternative.

The cost elements for each remedial alternative will be summarized in the cost analysis section of the CMS report. In accordance with USEPA guidelines, the cost estimates provided for each alternative will reflect actual costs with an accuracy of -30 to +50%. Most costs will be discounted over 30 years. Indirect costs will include an overhead labor rate of 45% with an additional 15% administration fee on all direct costs. A 10% profit will be added to all labor and materials. A 5% to 15% contingency on all labor and materials will be assumed. A 6% design fee will be used.

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3.0 BACKGROUND INFORMATION

The following briefly discusses information collected as part of the RFI for the apron area. Even though the fluvial deposits groundwater beneath the entire Northside comprises AOC A, the focus of the CMS will be the apron area and previously investigated SWMUs on or near the apron. SWMUs within AOC A warranting corrective measures include SWMUs 7, 15, 18, and 21 due to the chlorinated solvents and benzene identified in the fluvial deposits groundwater. Site conditions and contaminants in the fluvial deposits at the apron area are similar to those in other areas of the Northside; however, the contamination at the apron area is more extensive and appears to have the greatest potential to reach the base boundary. Therefore, the CMS will be performed using information collected from the apron area with the understanding that remedies identified for this area would most likely be appropriate for the other isolated areas.

3.1 Site Description

AOC A is collectively made up of the following thirteen SWMUs and sites on the Northside of NSA Mid-South:

SWMU 1	Fire Department Drill Area
SWMU 3	Building N-121 Plating Shop Dry Well
SWMU 5	Aircraft Fire Fighting Training Facility
SWMU 7	Building N-126 Plating Shop Dry Well
SWMU 8	Cemetery Disposal Area
SWMU 10	Demolition/Construction Debris Landfill
SWMU 15	Building N-94 Underground Tank Farm
SWMU 18	Building N-112 Underground Waste Tank
SWMU 21	Building N-10 Underground Waste Tank
SWMU 27	Northside Sewage Treatment Plant

SWMU 40 Salvage Yard No. 1

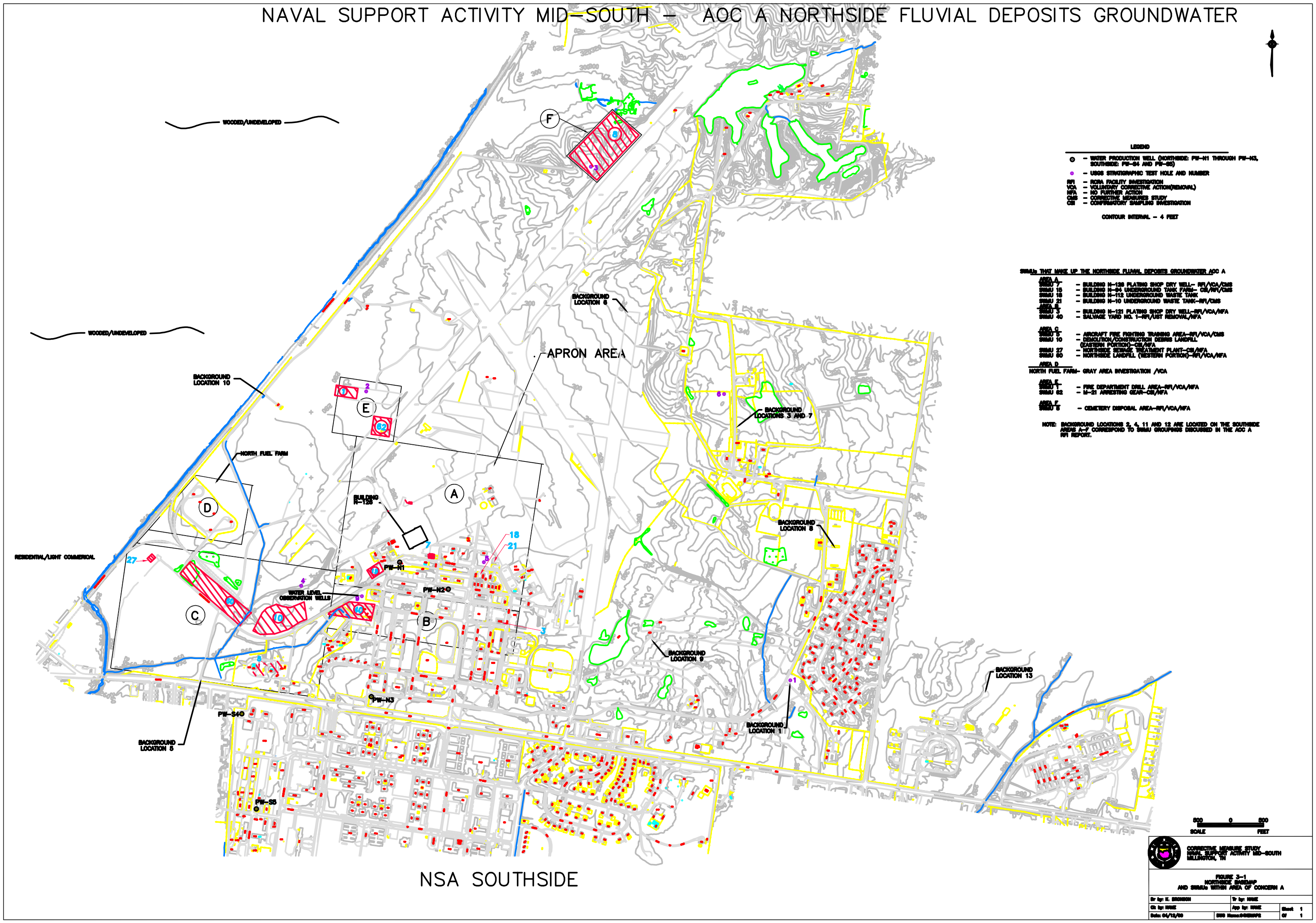
SWMU 60 Northside Landfill

SWMU 62 M-21 Arresting Gear

North Fuel Farm

Background Location 5

A base map of the Northside and SWMUs within AOC A where fluvial deposits groundwater data have been collected through earlier RFIs or Confirmatory Sampling Investigations (CSI) is provided in Figure 3-1. Most of the SWMUs identified for RFI or CSI characterization have been investigated and reports have been completed for them. The one exception is Assembly A, SWMU 7 (Building N-126 Plating Shop Dry Well), which required RFI characterization. During the initial stages of investigation, it became apparent that contamination associated with the dry well was minimal. The focus of the investigation changed to a grassy area south of the dry well when a former Building N-126 employee reported that chlorinated solvent waste had been discarded onto the ground there. Chlorinated solvents detected in the fluvial deposits groundwater in this area and subsequent interviews with Navy personnel regarding other known and suspected solvent disposal areas resulted in expanding the investigation to include an extensive area beneath the Northside's aircraft parking apron and taxiways over a two-year period. At the conclusion of the two-year investigation, chlorinated solvents were identified beneath much of the area; however, these contaminants could not be traced to an individual SWMU but appeared related to multiple small sources. The RFI intended for SWMU 7, evolved into what is therefore more appropriately named in this report as the apron area, which is the largest impacted area within AOC A. Furthermore, following the removal of the dry well in September 18, 1996, no further action was required at SWMU 7.


NAVAL SUPPORT ACTIVITY MID-SOUTH - AOC A NORTHSIDE FLUVIAL DEPOSITS GROUNDWATER
LEGEND
- WATER PRODUCTION WELL (NORTHSIDE: PW-N1 THROUGH PW-N3, SOUTHSIDE: PW-S4 AND PW-S5)
- USGS STRATIGRAPHIC TEST HOLE AND NUMBER
RFI - RCRA FACILITY INVESTIGATION
VCA - VOLUNTARY CORRECTIVE ACTION(REMOVAL)
NFA - NO FURTHER ACTION
CMS - CORRECTIVE MEASURES STUDY
CSI - CONFIRMATORY SAMPLING INVESTIGATION
CONTOUR INTERVAL - 4 FEET
SWMUs THAT MAKE UP THE NORTHSIDE FLUVIAL DEPOSITS GROUNDWATER AOC A
AREA A
SWMU 7 - BUILDING N-126 PLATING SHOP DRY WELL- RFI/VCA/CMS
SWMU 15 - BUILDING N-94 UNDERGROUND TANK FARM- CSI/RFI/CMS
SWMU 18 - BUILDING N-112 UNDERGROUND WASTE TANK
SWMU 21 - BUILDING N-10 UNDERGROUND WASTE TANK-RFI/CMS
AREA B
SWMU 3 - BUILDING N-121 PLATING SHOP DRY WELL-RFI/VCA/NFA
SWMU 40 - SALVAGE YARD NO. 1-RFI/UST REMOVAL/NFA
AREA C
SWMU 5 - AIRCRAFT FIRE FIGHTING TRAINING AREA-RFI/VCA/CMS
SWMU 10 - DEMOLITION/CONSTRUCTION DEBRIS LANDFILL (EASTERN PORTION)-CSI/NFA
SWMU 27 - NORTHSIDE SEWAGE TREATMENT PLANT-CSI/NFA
SWMU 60 - NORTHSIDE LANDFILL (WESTERN PORTION)-RFI/VCA/NFA
AREA D
NORTH FUEL FARM- GRAY AREA INVESTIGATION /VCA
AREA E
SWMU 1 - FIRE DEPARTMENT DRILL AREA-RFI/VCA/NFA
SWMU 62 - M-21 ARRESTING GEAR-CSI/NFA
AREA F
SWMU 8 - CEMETERY DISPOSAL AREA-RFI/VCA/NFA
NOTE: BACKGROUND LOCATIONS 2, 4, 11 AND 12 ARE LOCATED ON THE SOUTHSIDE AREAS A-F CORRESPOND TO SWMU GROUPINGS DISCUSSED IN THE AOC A RFI REPORT.
WOODED/UNDEVELOPED
WOODED/UNDEVELOPED
RESIDENTIAL/LIGHT COMMERCIAL
APRON AREA
NORTH FUEL FARM
BUILDING N-126
WATER LEVEL OBSERVATION WELLS
BACKGROUND LOCATION 10
BACKGROUND LOCATION 6
BACKGROUND LOCATIONS 3 AND 7
BACKGROUND LOCATION 8
BACKGROUND LOCATION 9
BACKGROUND LOCATION 1
BACKGROUND LOCATION 5
BACKGROUND LOCATION 13
A
B
C
D
E
F
PW-N1
PW-N2
PW-N3
PW-S4
PW-S5
NSA SOUTHSIDE
500 0 500
SCALE FEET
CORRECTIVE MEASURE STUDY
NAVAL SUPPORT ACTIVITY MID-SOUTH
MILLINGTON, TN
FIGURE 3-1
NORTHSIDE BASEMAP
AND SWMUs WITHIN AREA OF CONCERN A
Dr by: K. BRONSON
Tr by: NAME
Ck by: NAME
App by: NAME
Sheet 1
Of 1
Date: 04/12/00
DWG Name:04NBMAP2

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AOC A was designated after the apron-area investigation was underway and the numerous plumes within the fluvial deposits groundwater were identified. At that point, the BCT decided that a holistic approach was needed to evaluate the contamination and expedite the CMS process. Designating the fluvial deposits groundwater beneath the entire Northside as an AOC and comprehensively addressing the contamination rather than on a site-specific basis would ultimately speed the property transfer to the City of Millington.

3.2 Site Geology and Hydrogeology

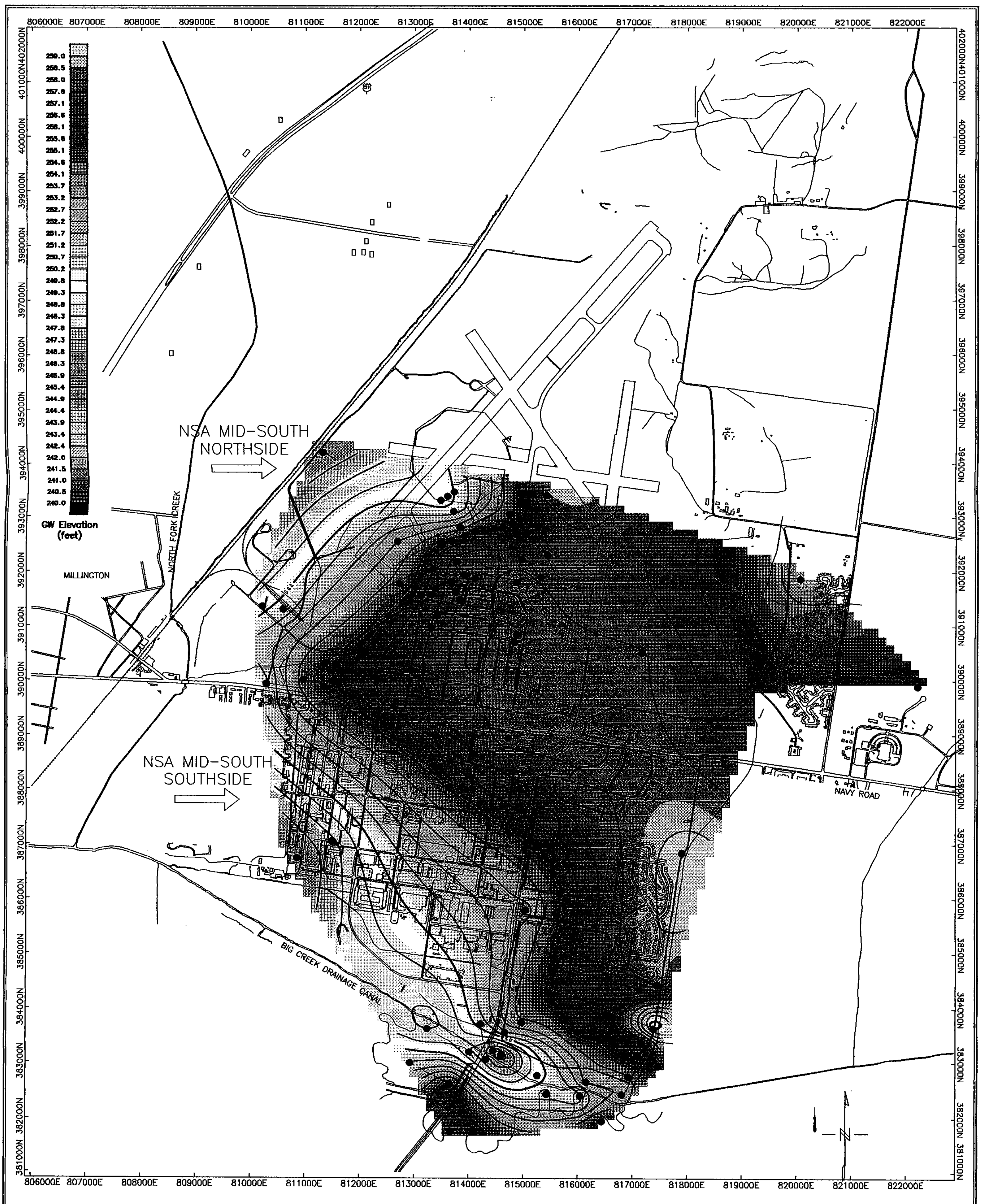
The principal stratigraphic units investigated during the AOC A RFI in descending order are: the loess of Pleistocene age, the fluvial deposits of Pleistocene to possibly Pliocene age, and the upper units of the Claiborne Group, specifically the Cockfield and Cook Mountain Formations of Eocene age, which are the one confining unit to the Memphis aquifer (Carmichael et al., 1997). The two principal groundwater units beneath NSA Mid-South are the alluvial-fluvial deposits aquifer, the most significant surficial aquifer, and the Memphis aquifer, the principal source of municipal water in the Memphis area. Groundwater in these two aquifers is hydraulically separated by the Cockfield and Cook Mountain Formations confining units, which range from about 30 to 230 feet thick.

The fluvial deposits beneath the airfield apron area are composed of poorly sorted sand and gravel with minor amounts of clay as interstitial material, and lenses generally no more than a few inches thick. Fine to medium sand is present in the upper sections of the fluvial deposits, coarsening with depth. Gravel occurs as lenses at various horizons in the fluvial deposits but is more common in the lower part of the unit. The thickness of the fluvial deposits, all of which is saturated, ranges from 26 to 64 feet.

The fluvial deposits are overlain and confined or semi-confined by loess, a relatively low-permeability unit composed of silt and clayey silt that ranges from 25 to 45 feet in thickness. A perched groundwater zone is present in the loess throughout most of the facility and varies from 4 to 8 feet below land surface. However, this perched groundwater zone is absent beneath much of the apron, where recharge is inhibited by the large area of concrete pavement. The base of the fluvial deposits (70 to 100 feet below land surface) is underlain by the Cockfield Formation, the lower confining unit for the fluvial deposits aquifer. The Cockfield Formation consists of interbedded sand, clay, silt, and lignite. Water levels in the Cockfield Formation are also confined and essentially equal to those in the fluvial deposits.

The Cook Mountain Formation, which contains the most aerially extensive clay in the upper part of the Claiborne Group in Shelby County, serves as part of the lower confining unit for the fluvial deposits aquifer and the upper confining unit for the Memphis aquifer. The Cook Mountain Formation at NSA Mid-South consists predominantly of clay and silt; however, minor lenses of silty fine sand may be present locally. Geophysical logs from municipal supply wells indicate the Cook Mountain Formation ranges in thickness from 10 to 60 feet (Carmichael et al., 1997).

In October 1998 and 1999, EnSafe measured groundwater elevations from select Northside and Southside monitoring wells completed in the upper fluvial deposits to generate the computer-contoured potentiometric maps for the base shown in Figures 3-2 and 3-3. Groundwater flow in the upper part of the fluvial deposits is shown in Figure 3-2 to flow radially away from three contoured mounds represented by the warmer colors. On Figure 3-3, groundwater flow is shown to flow radially away from a south to northwest contoured ridge. The flow direction on the Southside is primarily south, southwest, and west, and generally toward the Big Creek Drainage Canal that borders the Southside. On the Northside, the fluvial deposits flow north to northwest.



PLOT SUMMARY
- Groundwater elevation data collected Oct. 1998
- Dark gray dots show control data for this plot
- CAD drawings: 106LHWAT.DXF, 106LHBLD.DXF
- Plot file 101.P01 generated via Geosoft 01-11-00

Figure 3-2

POTENTIOMETRIC MAP, 10/98
Upper Fluvial Deposits Groundwater

AOC A - Northside Fluvial Groundwater
Corrective Measures Study (Rev.3)
NSA Mid-South

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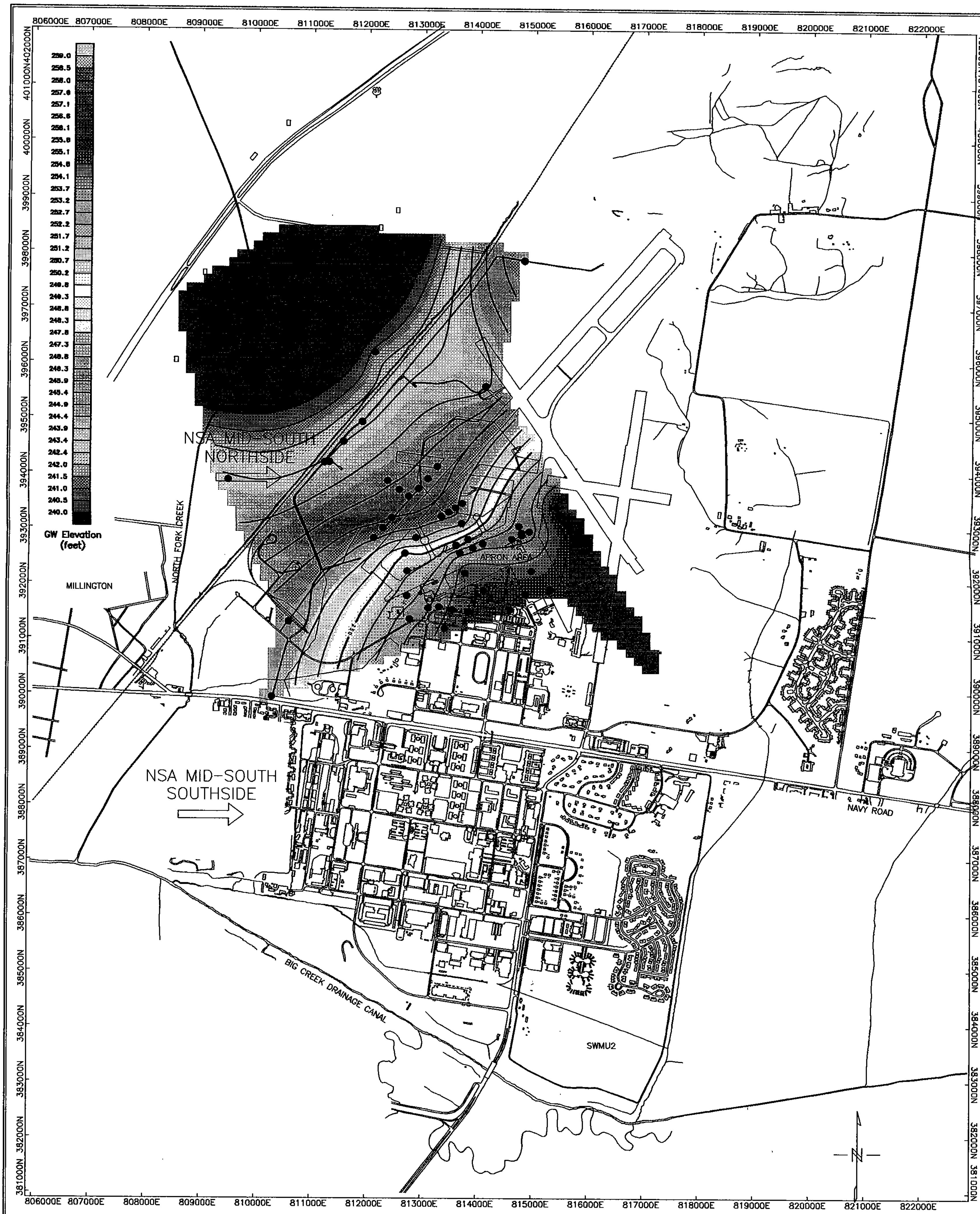

PLOT SUMMARY
- Groundwater elevation data collected Oct. 1999
- Dark gray dots show control data for this plot
- CAD drawings: 106LHWAT.DXF, 106LHBLD.DXF
- Plot file 102.P01 generated via Geosoft 01-11-00

Figure 3-3

POTENTIOMETRIC MAP, 10/99
Upper Fluvial Deposits Groundwater

AOC A - Northside Fluvial Groundwater
Corrective Measures Study (Rev.3)
NSA Mid-South
Millington, TN

EnSafe Inc.

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Potentiometric data from the apron area indicate that groundwater in the fluvial deposits is confined and flows to the north and west with an average hydraulic gradient of 0.004 and 0.008 feet per foot. Results of an aquifer test of the fluvial deposits aquifer at the apron area estimated hydraulic conductivity (K_{xy}) as 5.3 feet per day (Robinson et al., 1997), which yields a groundwater velocity between 31 and 62 feet per year (using a 25% assumed effective porosity value and the above hydraulic gradients). Likewise, an aquifer test conducted in the fluvial deposits north of the runway produced an estimated hydraulic conductivity of 59 feet per day. Using this K_{xy} value with the flatter gradients north of the runway (0.0017 feet per foot) and the same effective porosity, the groundwater velocity is approximately 140 feet per year.

3.3 Nature and Extent of Fluvial Deposits Groundwater Contamination

A primary reason for designating the Northside fluvial deposits groundwater as an AOC was to expedite the CMS process through collectively evaluating all the SWMUs or contaminant source areas to the fluvial deposits groundwater. The apron-area investigation showed that numerous areas containing multiple volatile organic compounds (VOCs) are present beneath the apron at concentrations exceeding U.S. Environmental Protection Agency (USEPA) and Tennessee Department of Environment and Conservation (TDEC) maximum contaminant levels (MCLs), thus warranting corrective measures. The *RFI Report —Area of Concern A —Northside Fluvial Groundwater, Revision 2* (EnSafe, 2000) and *RFI Report Addendum — Area of Concern A —Northside Fluvial Groundwater, Revision 0* (EnSafe, 2000) presents all the fluvial deposits data collected in the apron area through July 1999. Additionally, the *RFI Report — SWMU 18, Revision 2* (EnSafe, 1999) presents fluvial deposit data for SWMU 18.

The fluvial deposits data set is large and cumbersome because of multiple SWMUs, multiple sampling events with varying analytical suites, and the monitoring of three zones within the fluvial deposits (upper, middle, and lower). Primary contaminants of concern identified in the fluvial deposits include: PCE, TCE, 1,2-DCE, 1,2-DCA, 1,1-DCE, 1,1-DCA, carbon tetrachloride, chloroform, vinyl chloride, and benzene. Since analytical summary tables for this data set are lengthy and are presented in the AOC A RFI report, they will not be included in this document. However, in an effort to describe the contaminant plumes and their ultimate fate and transport, information about the contaminant conceptual model that was presented in the AOC A RFI report is discussed below.

Contaminant Conceptual Model

According to the RFI, chlorinated solvents are widely distributed in the fluvial deposits groundwater, and the spatial distribution and chemical composition of the solvents are very complex, precluding a quick, intuitive interpretation. A contaminant conceptual model designed to provide interpretations of this complex data set was presented in the AOC A RFI Report. Most of the significant contamination is from PCE and TCE and their various daughter products.

The conceptual model encompasses features such as plume extent, migrating versus static plume boundaries, potential for offsite migration, contaminant longevity, and effectiveness of natural attenuation. The modeling process resulted in a reasonable and scientifically credible interpretation of the available data. However, many uncertainties existed at many stages of the process, so the results are by no means definitive. In particular, it is worth noting that each plume is inferred from only one to perhaps a dozen data points. This undersampling effect means that some plumes may have been missed, and the ones drawn may have many errors in depicted geometry or interrelationships with other plumes. Other errors may have come from incorrectly surmising the reason for differing contaminant signatures and/or myriad other factors. However, the proposed model is considered the best working theory that can be derived from the available data, and it is therefore useful in important decision-making processes to come.

Figures 3-4 and 3-5 show the interpreted plumes for the more prevalent solvents PCE and TCE, respectively. The color scheme is the same for each plot. Slight irregularities in contour/color lines are computer gridding artifacts and are not physically significant.

3.4 RFI Conclusions and Recommendations

The following conclusions and recommendations were outlined in the AOC A RFI Report and Addendum.

- Soil contaminants detected during the apron area RFI exceeding SSLs include the VOCs acetone, benzene, carbon tetrachloride, methylene chloride, TCE, and 1,1,1-TCE; the SVOCs benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, carbozole, and dibenz(a,h)anthracene;1 and the pesticides dieldrin and heptachlor epoxide. However, their frequency of detection and concentrations were low. The inorganics detected in soil exceeding both their RCs and SSLs include barium, cadmium, and nickel.

- The RFI identified benzene and TCE in the loess groundwater at concentrations exceeding their MCLs. These contaminants were local to a single monitoring well (007G01LS).

- Fluvial deposits aquifer characteristics vary significantly across the study area. An additional aquifer pump test conducted since submitting the original RFI report indicated that the hydraulic conductivity in the airfield infield, north of the runway, was an order of magnitude higher than a previously evaluated area southwest of Building N-126.

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NSA Mid-South
Millington, Tennessee

Figure 3-4
PCE Plume Map
AOC A - Northside Fluvial Groundwater
Corrective Measures Study (Rev. 3)

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NSA Mid-South
Millington, Tennessee

Figure 3-5
TCE Plume Map
AOC A - Northside Fluvial Groundwater
Corrective Measures Study (Rev. 3)

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- The apron area RFI and previous SWMU investigations at the apron have identified PCE, TCE, 1,2-DCE, 1,2-DCA, 1,1-DCE, carbon tetrachloride, chloroform, and benzene in the fluvial deposits groundwater at concentrations exceeding their MCLs. Vinyl chloride which has a MCL of 2 μg/L has been detected in monitoring well 007G07UF at concentrations of 2J, 10U, 10U, and 10U μg/L. Vinyl chloride is an intermediate biological daughter product of PCE/TCE. It is now known to degrade in oxic (oxygen-rich) environments, under iron(III) reducing conditions, and by various co-metabolic degradation processes (Chapelle, 1996). Since vinyl chloride was detected so sparsely in the fluvial deposits, it appears that it is degrading by all or some of the above biological processes before it accumulates. The apron area is the most impacted AOC A area.

- The source areas appear to be small and multiple, resulting in a mixture of contaminant types and a complex network of multiple and overlapping plumes. A source of chlorinated solvents in the unsaturated zone in the loess has not been identified. The maximum TCE concentration detected in the fluvial deposits groundwater during the RFI addendum was 4,400 μg/L at well 007G04LF (EnSafe, 2000). Further source evaluation conducted near this well during the CMS pilot study identified a maximum TCE concentration of 6,680 μg/L. However, these concentrations are below the 1% solubility for TCE (or 11,000 μg/L) that is generally the rule of thumb indicator for DNAPL.

- PCE, TCE, and carbon tetrachloride concentrations exceeded their MCLs in the fluvial deposits groundwater at the base property boundary, approximately 2,900 feet downgradient from the suspected source areas. However, concentrations attenuate to either below the detection limit or below their respective MCLs in the off-site monitoring wells, approximately 450 feet downgradient of the bases's northwest property boundary.

- The potential for cross-contamination between the fluvial deposits aquifer and the Memphis aquifer is extremely low given the thickness and low permeability of the Cockfield and Cook Mountain Formations separating the two aquifers.

- Data collected during the apron area RFI indicate the extent of identified groundwater contamination is limited vertically to the fluvial deposits. Groundwater samples collected from the deeper Memphis aquifer at the apron area have been free of VOCs and tritium, supporting the conclusion that this unit is not well connected hydraulically to the fluvial deposits groundwater. Furthermore, groundwater samples collected from the Cockfield Formation which together with the Cook Mountain Formation separates and confines the two aquifers, were also free of tritium and VOCs, further supporting the absence of vertical migration of solvent contaminants identified in the fluvial deposits.

- No current receptors of the fluvial deposits groundwater have been identified at or near NSA Mid-South. Many private shallow domestic wells in rural areas of Memphis and Shelby County have been completed in the fluvial deposits, but most have been abandoned or are not used as a drinking water source since public water supplies have been extended into these areas in the mid to late 1970s. The nearest domestic supply well screened in the fluvial deposits is approximately 6,000 feet north-northwest of the apron area. This well is inactive and has been included in the off-site wells for down-gradient monitoring.

- MCL exceedances identified in the apron area loess groundwater, primarily benzene at SWMU 15, will be addressed in a separate CMS for the Northside loess groundwater.

- Chlorinated solvent concentrations in the fluvial deposits aquifer will be addressed in the AOC A CMS. The aquifer parameters calculated in the airfield infield will be used in the CMS for contaminant transport modeling.

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4.0 INVESTIGATING AND EVALUATING POTENTIAL REMEDIES

As previously stated, the CMS portion of the RCRA corrective action process is designed to identify and evaluate remedial alternatives for contaminant releases that have been detected at a facility. The scope and requirements of a CMS are to be balanced with quickly implementing remedies and rapidly restoring contaminated media, both major goals of the RCRA corrective action process.

The study of evaluating environmentally protective remedies may be relatively straightforward at some SWMUs or AOCs, and may not require extensive evaluation of numerous remedial alternatives. The CMS should be tailored to fit the complexity and scope of the remedial situation presented at each SWMU or AOC. For example, if the environmental problems at a SWMU or AOC are limited to a small area of soil with low-level contamination, the CMS may be limited to a single remedial approach (such as dig and haul) known to be effective for such types of contaminants in soil. The general approach for alternative evaluation is the identification and screening of alternatives through goal development, technology identification and evaluation, and comparing alternative based on established criteria.

For sites with very extensive or highly complex environmental problems, it is likely that an assessment of several alternative remedial technologies or approaches will be needed. Sites with large volumes of concentrated wastes and contaminated soil may require several treatment technologies to achieve varying degrees of effectiveness (such as reduction of toxicity or volume), in conjunction with different types of containment systems for residuals. A given contaminant problem may have several different practicable approaches which offer varying degrees of long-term reliability. The numerous plumes associated with the Northside fluvial deposits groundwater add a degree of complexity to evaluating remedies for AOC A; therefore, several remedial approaches will be examined as a part of this CMS.

To simplify and expedite the CMS process, sites may be grouped by common criteria such as:

- Common disposal/release mechanisms
- Similar contaminants
- Comparable concentrations and/or risk-derived remediation levels
- Common impacted matrix
- Common hydrogeologic characteristics
- Physical proximity to one another
- Economies of scale

Addressing the entire Northside fluvial deposits groundwater in a single CMS is an example of this grouping concept.

4.1 Identification, Screening, and Development of Corrective Measure Technologies

Generally, engineering practice and experience is used to identify which of the corrective action technologies appear most suited to each SWMU or AOC. The initial steps in assembling corrective measures technology alternatives is the review of the RFI results, corrective action objectives, and identification of technologies applicable to corrective measures of each SWMU/AOC or group of SWMUs/AOCs. Selection of corrective measures technologies is based on site-, waste- and technology-specific characteristics using current literature, vendor information, USEPA's treatability databases, technology databases, guidance documents and handbooks, and experience in developing alternatives for similar sites and releases.

The initial step in identifying corrective measures technologies is to group site-specific characteristics into impacted media types, soil/sediment/sludge, groundwater/surface water, and air. The second step is to group similar contaminant types, volatiles, semivolatiles, fuels, and inorganics. Thirdly, elements of reliability, cleanup time, cost, and operation and maintenance need to be considered, as well as advantages and disadvantages. The fourth step is to screen technologies using these general parameters. Table B-1 of Appendix B presents a screening matrix of treatment technologies that will be used to help identify and screen potential remedial technologies for the Northside fluvial deposits groundwater. This matrix was developed using *Remedial Technologies Screening Matrix and Reference Guide*, Second Edition, prepared by the Department of Defense Environmental Technology Transfer Committee (October 1994), as well as experience by personnel with EnSafe. Table B-2 describes each technology listed in Table B-1.

4.2 Development of Corrective Measure Alternatives

Based on engineering practice and experience, corrective measures technologies will be assembled into alternatives that may meet the corrective action objectives. Each alternative may consist of an individual technology or a combination of technologies used in sequence (i.e., treatment train). Depending upon site-specific situations, different alternatives may be considered for separate areas of the facility. Since no source areas have been located at AOC A, the areas with the highest contaminant concentrations will be defined as source areas for evaluation purposes. To further assist in the development of corrective measures alternatives, contaminants found in the Northside fluvial deposits groundwater have been grouped into the following categories:

- Chlorinated volatiles (PCE, TCE, 1,2-DCE, 1,2-DCA, 1,1-DCE, 1.1-DCA, carbon tetrachloride, vinyl chloride, and chloroform)

- Nonchlorinated volatiles (benzene)

Using these contaminant groupings and the identified technologies, a list of potential corrective measure technologies is developed. Table 4-1 lists removal, containment, and disposal technologies commonly used for addressing groundwater contamination; Table 4-2 lists proven treatment technologies for contaminant categories found in the Northside fluvial deposits groundwater. The BCT has identified three remedial technologies/approaches (monitored natural attenuation [MNA], anaerobic-aerobic [A-A] sequential treatment, and groundwater recovery and treatment/disposal) that should be included among those evaluated. The following section describes how these technologies will be fully evaluated. Other technologies or remedial approaches may be identified during the CMS. If so, an addendum to this work plan describing how these additional technologies or remedial approaches will be evaluated and submitted to the BCT.

Table 4-1
Removal/Containment/Disposal Options

Removal Action	Groundwater
Removal	Groundwater extraction (trenches and/or recovery wells)
Containment	Slurry wall Gradient controls Long-term monitoring Intrinsic remediation/natural attenuation
Disposal	POTW NPDES discharge Land application

Notes:
POTW — Publicly Owned Treatment Works
NPDES — National Pollutant Discharge Elimination System

Table 4-2
Treatment Technology Options

Contaminant Type	Groundwater
Chlorinated volatiles	Monitored Natural Attenuation Bioremediation Pump and Treat
Nonchlorinated volatiles	Monitored Natural Attenuation Bioremediation Pump and Treat

Monitored Natural Attenuation (MNA)

Natural attenuation is the combined effect of various physical, chemical, and biological processes that act to reduce a contaminant's toxicity, mobility, and mass in the subsurface. Physical processes include advection, dispersion, adsorption, and volatilization. Chemical processes include chemical oxidation and hydrolysis, while biological processes include microbially mediated destruction of contaminants. Physical processes are commonly referred to as nondestructive because they reduce contaminant concentrations and/or mobility without reducing contaminant mass in an aquifer. Chemical and biological processes are commonly referred to as destructive processes because they actually reduce the contaminant mass in an aquifer.

General Evaluation Approach

The evaluation of natural attenuation as a remedial alternative involves an understanding of how natural physical, chemical, and biological processes work to reduce contaminants to concentrations that protect human health and the environment. An evaluation of natural attenuation requires adequate site hydrogeological, chemical, and microbial characterization; and using this data to assess and demonstrate the potential of natural attenuation at a site.

The following is the sequential procedure to evaluate natural attenuation:

- Review available site hydrogeological, geochemical, and contaminant data.

- Perform preliminary screening of the site using geochemical data to assess the potential for natural attenuation.

- Simulate the natural attenuation process using site data and an analytical or numerical fate-and-transport model.

- Make a theoretical determination (based on model simulations) on the nature of the plume using appropriate assumptions to estimate if the plume(s) is/are at steady state, receding, or expanding.

- Assess the economics of natural attenuation.

- Evaluate whether natural attenuation can reach cleanup goals (solely or in combination with another remedy), and if so, in what timeframe. In the absence of an available laboratory method to measure a sustainable natural carbon source for reductive dechlorination, empirical calculations will be made to estimate the if the natural organic carbon is sufficient to sustain reductive dechlorination (Wiedemeier et al., 1996).

- Develop a groundwater monitoring program to demonstrate natural attenuation and verify the generated simulation model.

- Establish a remedial contingency in the event monitoring indicates that natural attenuation is insufficient to remediate groundwater.

Review of Site Data

Data collected during site characterization are used to evaluate the site for the potential for natural attenuation and to simulate fate-and-transport modeling. Site characterization at the apron area groundwater location has been performed as part of the RFI. The site characterization includes the following data:

- Location and type of chlorinated solvent plumes in the groundwater at the apron area

- Location, extent, and concentrations of dissolved contaminants in the groundwater collected interactively over the period of the investigation

- Geochemical data collected in conjunction with the RFI

- Hydrogeological parameters such as soil type, thickness of the geological deposits, thickness of the aquifer(s), hydraulic conductivity, hydraulic gradient, porosity, and groundwater velocity

Criteria for Preliminary Screening of Geochemical Data

Geochemical data are to be used in the preliminary screening process that evaluates the potential of the biodegradation component of natural attenuation at the site. The screening process is based on the concept that natural geochemical conditions influence natural microbial activity and the resulting natural biodegradation causes changes in the groundwater chemistry which can be measured by indicator parameters. These indicator parameters are listed below:

- Dissolved Oxygen
- pH
- Redox Potential
- Sulfide
- Ferrous Iron
- Total Iron
- Nitrate
- Sulfate
- Methane
- Alkalinity
- Chloride
- Total Organic Carbon

The screening process uses a scoring system that allocates points to each specific geochemical parameter. A scoring table has been established and is detailed in U.S. EPA's *Draft Region 4 Approach to Natural Attenuation of Chlorinated Solvents* (USEPA, 1997). The scoring table and the total points scored for a particular site can be used to interpret the extent of evidence of natural biodegradation. Results of the analysis of groundwater geochemistry and the potential for natural biodegradation of chlorinated solvents at the apron area will be detailed in the CMS Report.

Modeling/Simulation of the Natural Attenuation Process

Simulation of natural attenuation is an important step that provides quantified estimates of its potential. Simulation incorporates the effects of destructive (biological) and non-destructive (advective, dispersive, and sorptive) mechanisms. An analytical or numerical fate-and-transport model as a simulation tool estimates:

- The distance the contaminant will travel before it is reduced to the target clean up levels
- The location of groundwater monitoring wells for the natural attenuation evaluation (to be described in the CMS Report)

Site geological and hydrogeological information, contaminant concentrations, and geochemistry will be used as input data in a model to simulate processes that estimate the potential for natural attenuation. The non-destructive parameters to be used for simulation (advection, dispersion, and adsorption) can be estimated as follows:

Advection is a function of the average groundwater velocity. Groundwater velocity at the site has been estimated from site-specific values of hydraulic conductivity, hydraulic gradient, and effective porosity which are available from the RFI.

Dispersion is a difficult parameter to measure in the field because of the ambiguity in separating the dispersive process from other transport processes in the subsurface. However, for particular sediment types and given lengths of plumes or distances from source, literature values are available that can be satisfactorily used in a fate-and-transport model. Using literature estimates, longitudinal, transverse, and vertical dispersivity can be estimated. Gelhar, et al., (1992) and Xu and Eckstein (1995) have described empirical formulae to estimate these dispersive coefficients.

Adsorption coefficients can also be estimated using data on organic carbon content obtained during the RFI. The adsorption coefficient, K_d, can also be estimated from literature values of solubility of the contaminant and the octanol-water partitioning coefficient, K_{ow}. Retardation factors can then be calculated from the estimated K_d value and RFI-determined soil bulk density and porosity.

The proposed model to be used for simulation of the natural attenuation process is BIOCHLOR (Aziz, 1999). BIOCHLOR will be used to quantify the degradation given the singular nature of the contamination, evidence from biodegradation, and size and simplicity of the site. BIOCHLOR beta v1.0 is a spreadsheet-based (Microsoft Excel) screening tool used to gauge the natural attenuation of dissolved chlorinated solvents (tetrachloroethene, trichloroethene, dichloroethene, and vinyl chloride). BIOCHLOR can be used to simulate one-dimensional advection, three-dimensional dispersion, linear adsorption, and biodegradation by reductive dechlorination. It is based on a semi-analytical solution developed by Domenico (1987). In using BIOCHLOR, several assumptions must be made concerning the system to be modeled:

- Aquifer conditions are anaerobic.
- Biodegradation occurs as a sequential first-order decay process.
- Biodegradation occurs only in the aqueous phase.
- The aquifer and flow field are homogeneous and isotropic.
- Groundwater velocities are fast enough that molecular diffusion can be ignored.
- Adsorption is a reversible process that can be represented by a linear isotherm.

BIOCHLOR is limited in the following ways:

- The model should not be applied in complicated flow systems, such as those next to pumping systems.

- The model should not be applied where vertical contaminant transport is important.

- The model should not be applied where the site hydrogeology changes dramatically over the model domain.

BIOCHLOR outputs graphical representations of chlorinated compound concentrations produced without biodegradation, as a result of sequential first-order biodegradation, both as a function of distance from the source. Site-specific field data can also be plotted for comparison. Additional graphical output includes a two-dimensional representation of the contaminant plume with or without taking into account biodegradation. The change in plume mass due to biodegradation can also be calculated. A utility is also included to compare the reduction in contaminant mass produced by biodegradation with that of a pump and treat system. The model and its application will be described in the CMS Report. The specific locations to be modeled within the apron area and the results of the modeling effort will also be described in the report. The results of the modeling study will be used to locate natural attenuation groundwater monitoring wells needed for the evaluation and implementation of natural attenuation.

In addition to the above, other applicable elements of EPA's *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater* (USEPA, 1998) will be used to evaluate natural attenuation.

Enhanced Bioremediation

Anaerobic-aerobic (A-A) sequential groundwater treatment, also known as "two-zone interception treatment," is designed for enhanced in-situ bioremediation of chlorinated solvent contamination in groundwater. The objective of this alternative is to degrade PCE and TCE sequentially to innocuous gaseous and liquid end-products, once an anaerobic zone upgradient of an aerobic zone within a VOC contaminated groundwater plume is created. This has been demonstrated as an Emerging Technology under USEPA's Superfund Innovative Technology Evaluation (SITE) Program.

Most chlorinated solvents at contaminated groundwater sites are amenable to biodegradation. However, in contrast to petroleum hydrocarbons, chlorinated solvents are more sensitive to groundwater oxidation-reduction potentials (redox), availability of natural organic carbon or anthropogenic organic substrates (benzene, toluene, ethyl benzene, xylenes [BTEX] contamination or other man-made carbon sources), and natural groundwater electron acceptors such as dissolved oxygen, nitrate, sulfate, and carbon dioxide.

While petroleum hydrocarbons can serve as a primary organic substrate (food source that provides energy) or electron donor for microorganisms, chlorinated solvents — particularly the highly chlorinated solvents such as PCE and TCE — are not a direct food or energy source. PCE and TCE serve more as electron acceptors, similar to the role played by oxygen, nitrate, sulfate, and carbon dioxide in BTEX or natural organic carbon degradation. The lesser chlorinated solvents such as 1,2-Dichloroethene (1,2-DCE) and vinyl chloride (VC) (the biodegradation breakdown products or daughter compounds of PCE and TCE) are more likely to serve as primary organic substrates or electron donors and are more amenable to biodegradation in the presence of oxygen. In other words, anaerobic or reduced oxygen conditions (absence of dissolved oxygen) are more suitable for PCE and TCE degradation. Moreover, the lower the aquifer's oxygen content, the more readily PCE and TCE will degrade.

The anaerobic or aerobic state of the aquifer can be estimated from redox measurements. The lower the redox potential of the aquifer (measured in millivolts) of the aquifer the more anaerobic or strongly reducing the aquifer is. In general, redox potentials less than 50 millivolts represent anaerobic reducing conditions. If redox measurements near the PCE and TCE plume are greater than 50 millivolts, nutrients (nitrate and phosphate fertilizers) and substrate (organic carbon) can be added to increase biological respiration and drive the system into anaerobic or strongly reducing conditions. Generally, enough carbon is added to both create anaerobic conditions and serve as a food source during subsequent reductive degradation of highly chlorinated solvents such as PCE and TCE. Conversely, if redox measurements near the DCE and VC plume are less than 50 millivolts, air sparging techniques can be used to increase oxygen availability and allow maximum biological consumption of substrates such as DCE and VC.

By creating an anaerobic zone upgradient of an aerobic zone within a VOC-contaminated groundwater plume, a sequential anaerobic-aerobic system is established that is capable of sequentially degrading PCE and TCE to innocuous gaseous end-products. Moreover, flow through these zones can be accelerated by placing a low-flow extraction well downgradient of the aerobic zone and reinjecting pumped water upgradient of the anaerobic zone. Figure 4-1 is a three-dimensional conceptual remedial technology schematic layout of a typical A-A treatment system.

Anaerobic Zone

An anaerobic zone is created by pumping groundwater from downgradient extraction wells and amending it with carbon and other nutrients before reinjecting it into upgradient wells. The pumped groundwater is first sent to an aboveground chemical amendment system where carbon and nutrients are added. Amended groundwater is then reinjected into the aquifer. The amendments are designed to provide a ready food source to stimulate microbial respiration which utilizes all available oxygen in the pumped groundwater. This recirculation process of extraction and reinjection continues until an anaerobic zone gradually is created near the reinjection wells. Highly chlorinated solvents such as PCE and TCE are amenable to reductive dechlorination (biological removal of chlorine) under anaerobic conditions. In other words, once the anaerobic zone is established, microorganisms will turn to sources other than oxygen, such as chlorinated VOCs, in order to complete respiration.

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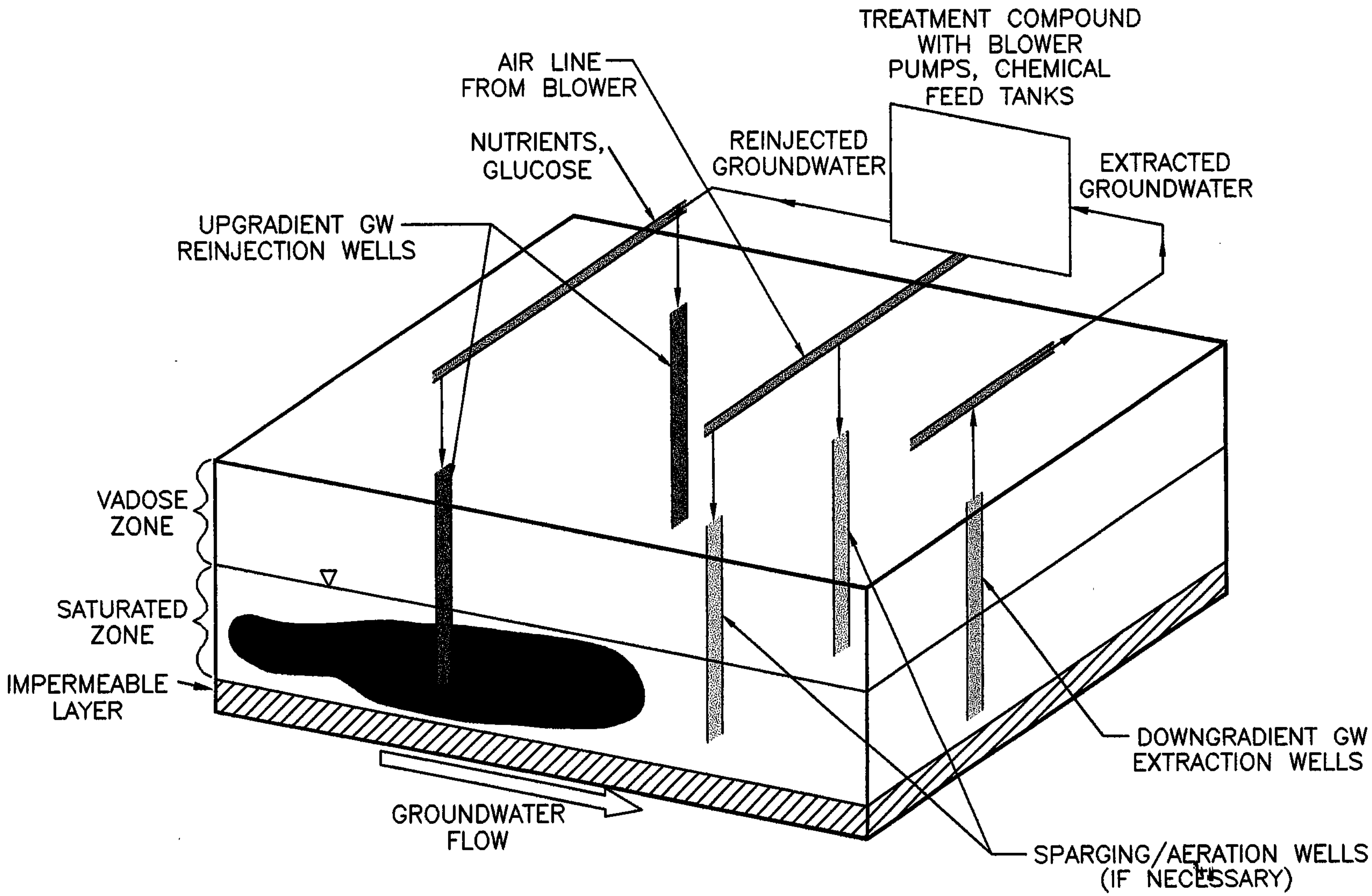

NOT TO SCALE

CORRECTIVE MEASURE STUDY NAVAL SUPPORT ACTIVITY MID-SOUTH MILLINGTON, TN	FIGURE 4-1 CONCEPTUAL REMEDIAL TECHNOLOGY SCHEMATIC FOR ANAEROBIC-AEROBIC SEQUENTIAL GROUNDWATER TREATMENT
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Aerobic Zone

Anaerobic reductive dechlorination results in the formation of lesser-chlorinated daughter products, namely 1,2 cis-DCE and VC. Because these compounds break down more readily in an aerobic environment, an aerobic zone is created near the downgradient extraction wells by injecting air into the aquifer via sparging wells connected to an aboveground blower. The sparging wells will be located about 100 feet downgradient of the reinjection wells. Sparging is generally performed intermittently based on groundwater dissolved oxygen (DO) concentrations in area monitoring wells. If required, carbon and nutrients can also be added to the air sparging wells to enhance aerobic degradation of 1,2 cis-DCE and VC. Aerobic degradation of VC results in the formation of innocuous gaseous end-products such as ethylene and ethane.

General Evaluation Approach

Pilot-scale studies will be used to evaluate A-A sequential groundwater treatment. Though this technology is based on fundamental microbial principles, it has been applied at only a few sites in the United States and is considered an innovative technology. Furthermore, this technology is easily enhanced or inhibited by inherent chemical, geological, and hydrogeological variables difficult to reproduce in a laboratory. Therefore, a pilot-scale treatability study is needed to assess its effectiveness at AOC A.

Pilot-scale systems will be installed in the AOC A plume areas containing the highest concentrations of TCE. One system will be installed in the area southeast of Building N-126. This system will be similar to traditional A-A systems which accelerates groundwater flow using an extraction well downgradient of the aerobic zone and re-injection wells upgradient of the anaerobic zone. Details of this system can be found in the *A-A Sequential Remediation Treatability Study Work Plan* (EnSafe, November 1999).

The other system will be installed in the area once occupied by Building N-6. This system will inject vegetable oil directly into the contaminated aquifer using conventional wells. This will allow significant volumes of carbon to be added and to become well distributed in the aquifer. The separate phase nature of vegetable oil will allow for slow dissolution into groundwater, thus making it a slow release carbon source. Details of this system can be found in the *Draft Work Plan for Field Application to Enhance In-situ Bioremediation of Chlorinated Solvents Via Vegetable Oil Injection at Site N-6* (Parsons, March 2000).

Groundwater analytical results from these pilot studies will be evaluated to estimate the effectiveness of the anaerobic-aerobic technology. Measuring TCE and PCE and concentrations of their breakdown components will provide an estimate of the amount of contaminant remediated.

Pump and Treat

The objective of this alternative is to eliminate or reduce the spread of contaminants in groundwater by the use of hydraulic containment control. Groundwater extraction systems are used for hydraulic control and involve the pumping of groundwater via a series of wells surrounding the source or in the immediate plume area to manipulate the natural groundwater gradient in such a way as to inhibit the migration of contaminants. The design objective in the hydraulic control of groundwater contamination can be to generally alter the groundwater flow regime to prevent further migration, to reduce the rate of plume migration by removing contaminants, or to confine the plume to a potentiometric low. Aboveground treatment units become necessary to handle the contaminated water pumped by the wells.

Groundwater pump and treat (P&T) methods use one or more extraction wells to remove dissolved contaminants by developing a hydraulic capture zone to encompass the contaminant plume under steady-state flow conditions. For a single well, the set of all horizontal groundwater flow paths that intercept the well over an infinite period of time defines the steady state capture zone of the well and, in theory, groundwater and dissolved contaminants within this capture zone should be drawn to the well under continuous pumping.

Once contaminated groundwater has been pumped to the surface it will most likely be treated before being transferred to a publicly owned treatment works (POTW), a surface water body, etc. Aboveground treatment units are used to handle any contaminated water pumped by the wells. The most common physical treatment processes are: air stripping, ultraviolet oxidation (UV-OX), and carbon adsorption.

Air stripping is the physical process of transferring VOCs from water into air. Air stripping refers to the process of contacting air and groundwater under conditions and in relative quantities suitable to volatilize organic contaminants from the liquid phase. Air stripping involves introduction of the contaminated water to the top of the treatment system while a countercurrent air stream from the bottom of the system aerates the water as it is cascades down. Since most organics have vapor pressures much lower than that of water, they can be stripped by maximizing the surface area of the groundwater and then passing air over the water surface, causing a pressure drop at the air/water interface. The contaminants then travel from the higher pressure zone (water) to the lower pressure zone (air in motion). While doing so, contaminants convert to the vapor phase and they can then be removed. Older air-stripper designs used packed aeration towers consisting of randomly placed plastic or ceramic packing with high surface areas. The newer designs use perforated trays. The water flows down the trays as the air passes through the water on the trays. If the contaminated groundwater contains high concentrations of organics, air stripping is often used as the first step in a two-step process, which may also use carbon adsorption.

Three categories of contaminants can be identified as to their stripping ability: those which are not amenable to air stripping at all, those that are very easily stripped, and a transitional group for which air stripping design must be carefully optimized for good results. Basic to all groups of organic contaminants in the air stripping process is the mass transfer rate. The transfer rate of a compound is largely determined by its Henry's Law constant, which is the partition coefficient of the contaminant between the aqueous and gaseous phases. The difference between the actual contaminant concentration and the equilibrium concentration, predicted by the Henry's Law constant, provides the concentration gradient which drives the mass transfer process.

UV-OX treatment systems use ultraviolet radiation, ozone, and hydrogen peroxide to oxidize organics in water. The major components of a UV-OX system are the ultraviolet/oxidation reactor module, an air compressor/ozone generator module, a hydrogen peroxide feed system, and a catalytic ozone decomposition unit. Chemical oxidation is a process in which the oxidation state of a contaminant is increased while the oxidation state of the reactant is lowered. The electrons gained by the oxidizing agent are lost by the contaminant. Chemical oxidation is used when hazardous contaminants can be destroyed by converting them to nontoxic or less hazardous compounds. Contaminants are detoxified by actually changing their chemical forms. During operation of a UV-OX system, contaminated water first comes in contact with hydrogen peroxide as it flows through the influent line to the reactor. The water then comes in contact with the UV radiation and ozone as it flows through the reactor at a specified rate to achieve the desired hydraulic retention time. As the ozone gas in the reactor is transferred to the contaminated water, hydroxyl radicals are produced. The hydroxyl radical formation from ozone is catalyzed by UV radiation and hydrogen peroxide. Ozone that is not transferred to the contaminated water will be present in the reactor off-gas. This ozone is depleted by the ozone decomposition unit before being vented to the atmosphere. The treated water flows from the reactor for appropriate disposal.

Carbon Adsorption involves the preferential partitioning of substances from the gaseous or liquid phase onto the surface of a solid substrate (carbon). The process of adsorption involves separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. The adsorbing phase is the adsorbent, and the material concentrated or adsorbed at the surface of that phase is the adsorbate. A large specific surface area is preferable for providing large adsorption capacity, but the creation of a large internal surface area in a limited volume gives rise to large numbers of small sized pores between adsorption surfaces. The size of these micropores determines the accessibility of adsorbate molecules to the internal adsorption surface, so the pore size distribution of micropores is an important property for characterizing absorptivity of absorbents.

Activated carbon is used as an adsorbing phase to adsorb organics from contaminated groundwater. The contaminated water is passed over particles of carbon which have been prepared to provide a large surface area where the contaminants can be adsorbed. As a contaminated water stream passes through a confined bed of activated carbon, a dynamic condition establishes a mass transfer zone. This mass transfer zone is defined as the carbon bed depth required to reduce the contaminant concentration from the initial to the final level, at a given flow rate. As the mass transfer zone moves through a carbon bed and reaches its exit boundary, contamination begins to show in the effluent. This condition is classified as "breakthrough" and the amount of material adsorbed is considered the breakthrough capacity. Activated carbon is particularly effective in situations where both the concentration of contaminants and the flow rate is low.

General Evaluation Approach

To evaluate P&T technology, one must understand how hydrogeologic properties affect the efficiency of the groundwater extraction part of the process and evaluate the time needed to achieve groundwater cleanup using groundwater extraction. To evaluate the supplemental treatment of extracted groundwater, its necessary to know the chemical properties of the contaminants as well as influent and effluent requirements that will be needed.

A proposed procedure to evaluating P&T is:

- Review site hydrogeological and contaminant data
- Perform an analytical model simulation using aquifer pump-test data
- Assess the economics of the technology
- Evaluate whether the technology can reach cleanup goals, and if so, in what timeframe

Site Data

The apron area groundwater has already been characterized as part of the RFI. Data from the RFI will be used to evaluate P&T as a potential remediation technology.

Site data which will be used to evaluate P&T include:

- *Hydrogeological:* soil type, soil depths, permeability, lithology, depths to water-bearing zones, groundwater gradients and velocities in water-bearing zones, aquifer pump-test data, and hydraulic conductivity.

- *Chemical:* contaminants of concern identified in groundwater, their chemical properties and concentrations.

- *Interpreted:* location of contaminant plumes, their source areas, and extent.

Analytical Model Simulation

To properly interpret sampling and pumping-test data from monitoring and pumping wells and to estimate their potential effectiveness in remedial actions, it is important to clearly define the geometry of that portion of the aquifer contributing water to the well. Once this geometry has been defined several design parameters can be determined:

- The number of extraction wells needed to alter contaminant plume movement
- Extraction well construction details
- Extraction well pump type and size
- The concentration of contaminants (loading rates) that can be expected for supplemental treatment

The CAPZONE and GW-Path analytical flow models may be used to evaluate groundwater flow and theoretical drawdown within the fluvial deposits at the NSA Mid-South Northside AOC A. The models can be used to evaluate capture zones for groundwater recovery alternatives with respect to contaminant locations.

The CAPZONE analytical process integrates three software programs. CAPZONE, as the central program, estimates drawdowns at the intersections of a regularly spaced horizontal grid according to the Theis equation. The user may then either superimpose the drawdown grid on a uniform hydraulic gradient or on a regional potentiometric surface map to represent theoretical pumping conditions within the aquifer. CAPZONE may also be used to model image wells and superposition of drawdown, therefore facilitating analyses of a bounded aquifer or a well system with one or more recovery/injection wells.

As CAPZONE is based on the Theis equation, the following assumptions are inherent to the analysis:

- The aquifer is isotropic, homogeneous, and infinite
- Radial flow is bounded by nonleaky-confining layers
- The pumping well is fully-penetrating and has an unlimited diameter
- Extraction rates are constant

GW-PATH is a groundwater pathline and traveltime analysis program that computes the two-dimensional, steady-state velocity field at the intersections of a rectangular grid using distributions of hydraulic head, hydraulic conductivity, and effective porosity. Capture zones may be delineated using either forward- or reverse-particle tracking modules. GW-PATH receives CAPZONE output grids and uses them to track particles and analyze capture zone.

SURFER is the input/output program used to develop regional potentiometric surface maps of the aquifer system. SURFER is capable of contouring potentiometric surfaces using krieging, inverse-distance, or minimum curvature algorithms. Potentiometric surface maps will be contoured using the SURFER program. SURFER is also one of the output programs available to evaluate CAPZONE and GW-PATH data. SURFER is used to view or print CAPZONE grids for evaluation. SURFER also processes GW-PATH *.PLT files into *.DXF files. *.DXF files may then be imported into AUTOCAD for viewing and/or plotting.

The CAPZONE/GW-PATH methodology offers two distinct advantages over similar analytical methodologies, such as WHPA-RESSQC or DREAM. First, the CAPZONE/GW-PATH method can be used to evaluate drawdown superimposed on a regional potentiometric surface, to better represent actual aquifer conditions. Previously, superposition on a regional water-level map was only possible through use of a three-dimensional, finite-difference flow model such as MODFLOW. Second, calibration of CAPZONE/GW-PATH using theoretical and observed drawdowns on a regional potentiometric surface is facilitated through the use of SURFER utilities. Calibration of the CAPZONE model is achieved through a trial-and-error process in which pumping data are compared to theoretical drawdowns. The user may adjust aquifer parameters such as transmissivity and storativity and thus perform sensitivity analyses until the optimal match is found. Calibration is usually performed using both visual comparisons of pumping and theoretical data, as well as statistical analyses.

Input data required for CAPZONE analyses include aquifer parameters, pumping/injection well data, grid parameters, and either a uniform hydraulic gradient or a regional potentiometric surface map. These parameters are summarized in Table 4-3.

GW-PATH input parameters include definition of the flow domain, grid parameters, groundwater-flow parameters, and a hydraulic-head data file. If pathlines will be computed, the pathline type, start coordinates, and time increment must be provided. These parameters are summarized in Table 4-4.

Table 4-3
CAPZONE Input Parameters

Parameter Group	Parameter	Units	Definition
Units	Input Units	American or metric	The user must define the units which will be used throughout input.
Aquifer Parameters	Solution Method	none	User must select Theis, Hantush, or Jacob solution.
	Transmissivity	gpd/ft or m^2/d	User must input the transmissivity.
	Storativity	unitless	User must input the storativity.
	Confined/ Unconfined	none	User must define aquifer as confined or unconfined
	Saturated Thickness	ft or m	User must define the saturated thickness of the aquifer

Table 4-3
CAPZONE Input Parameters

Parameter Group	Parameter	Units	Definition
Pumping/Injection Well Parameters	Number of Wells	None	User must define the number of pumping/ injection wells to be analyzed.
	X,Y Coordinates	ft or m	The X and Y coordinates of each pumping well.
	Pumping/Injection Rate	gpd or l/d	The pumping or injection rate for each well (injection is negative).
	Pumping Duration	days	The duration of pumping for each well.
Grid Parameters	X,Y Start Coordinates	ft or m	X,Y start coordinates for grid.
	Nodes in X Direction	unitless	Number of grids in X direction.
	Increment in X Direction	ft or m	Delta X spacing between nodes.
	Nodes in Y Direction	unitless	Number of grids in Y direction.
	Increment in Y Direction	ft or m	Delta Y spacing between nodes.
Regional Potentiometric Map/ Hydraulic Gradient	Regional Potentiometric Map	None	The regional piezometric surface map upon which CAPZONE superimposes the theoretical drawdowns.
	Uniform Hydraulic Gradient	ft/ft or m/m	The gradient upon which CAPZONE superimposes the theoretical drawdowns.

Table 4-4
GW-PATH Input Parameters

Parameter Group	Parameter	Units	Definition
Flow Domain Parameters	Orientation	none	User must define either a horizontal (plane view) or vertical (cross-sectional) orientation.
	Length Units	ft or m	User must define units.
	Time Units	seconds, years, or days	User must define units.
	Plotfile Name	none	If the user wishes to generate a plot of the pathlines, a plotfile must be defined (*.PLT).
	Number of Nodes (X,Y)	none	The user must define the number of X and Y nodes in the grid.
	X,Y Start Coordinates	ft or m	The user must define the X and Y start coordinates.
	Increment in X Direction	ft or m	Delta X spacing between nodes.
	Increment in Y Direction	ft or m	Delta Y spacing between nodes.
Hydraulic Head Data File	File Name	unitless	The user must specify a hydraulic head file name to represent either a static or stressed piezometric surface on which to generate pathlines.
Pathline Analysis Parameters	Pathline Type/ Analysis Method	none	User must specify if forward or reverse pathlines will be used, or if capture zones will be identified.
	Start Coordinates	ft or m	The user must identify the start coordinates for pathline estimation.
	Number of Paths	none	The user must identify the number of pathlines to be used if delineating a capture zone.
	Total Time	years	The time duration of pathline analysis. Units must agree with those selected under flow domain parameters.
	Max/Min Time Step	years	The user must define the maximum and minimum time increments to be used in pathline estimation.
	Moves per Cell	none	The user must define the degree of resolution possible within a grid cell.

4.3 Evaluation of Corrective Measures Alternatives

Each alternative proposed will be evaluated according to five standards reflecting the major technical components of remedies, including cleanup of releases, source control, and management of wastes generated by remedial activities. The specific standards are provided below:

- Protection of human health and the environment
- Attainment of media cleanup standards set by the implementing agency
- Control of the source of releases so as to reduce or eliminate, to the extent practicable, further releases that may pose a threat to human health and the environment
- Compliance with any applicable standards for management of wastes
- Other factors

These standards are detailed in the following sections.

4.3.1 Protection of Human Health and the Environment

Corrective action remedies must be protective of human health and the environment. The degree of protection afforded by each alternative will be discussed in this section.

Remedies may also include measures that are needed to be protective of human health and the environment, although they are not directly related to media cleanup, source control, or management of wastes. For example, access controls and deed restrictions may be implemented to prevent contact with contaminated media while intrinsic or engineered remedial processes are monitored or augmented.

4.3.2 Attainment of Media Cleanup Standards Set by the Implementing Agency

Each alternative will be evaluated as to whether the potential remedy will achieve the PRGs. This evaluation will include an estimate of the time necessary for each alternative to meet these standards. Remedial goal options (RGOs) may be established where PRGs cannot be attained.

4.3.3 Control of the Sources of Releases

Although not anticipated for AOC A, source-control measures will be evaluated as part of the CMS to determine if they are necessary to control or eliminate further releases that may threaten human health or the environment. If a source-control measure is proposed, the report will discuss the technology to be implemented for the given site conditions and the reliability of the selected technology.

Source-control measures will be considered when it is necessary to stop further environmental degradation by controlling or eliminating further releases that may threaten human health or the environment. Without source-control measures, some efforts to clean up releases may be ineffective or at best will essentially involve a perpetual cleanup. In these cases, an effective source-control program may be essential to ensure the long-term effectiveness and protectiveness of the corrective action program.

Source-control measures may include all protective remedies to control the source. Such remedies may include partial waste removal, capping, slurry walls, in situ treatments and/or stabilization, and consolidation.

4.3.4 Compliance with Any Applicable Standards for Management of Wastes

For each alternative, the report will discuss how the specific waste-management activities will maintain compliance with all applicable state or federal regulations, such as closure requirements, land disposal restrictions, etc.

4.3.5 Other Factors

Five general factors will be considered as appropriate in selecting/approving a remedy that meets the standards listed above. These factors combine technical measures and management controls to address the environmental problems at the facility. The five general decision factors include:

- Long-term reliability and effectiveness
- Reduction in the toxicity, mobility, or volume of wastes
- Short-term effectiveness
- Implementability
- Cost

Long-Term Reliability and Effectiveness

The CMS will evaluate whether the technology or a combination of technologies has been used effectively under analogous site conditions, whether failure of any one technology in the alternative would have an immediate impact on receptors, and whether the alternative would have the flexibility to deal with uncontrollable changes onsite.

This criterion will assess the proposed useful life of the overall alternative and its component technologies. Useful life is defined as the length of time that the level of effectiveness can be maintained. Typically, most corrective measures technologies deteriorate with time. Deterioration can often be slowed through proper system operation and maintenance, but the technology may eventually require replacement to maintain effectiveness. The CMS will consider these issues.

Reduction in the Toxicity, Mobility, or Volume of Wastes

This criterion will be used to assess the degree to which each alternative reduces the toxicity, mobility, or volume of wastes. In general, preferred remedies employ treatment and can eliminate (or substantially reduce) the potential for contaminated media to cause future environmental releases or other risks to human health and the environment. Estimates of how much the corrective measures alternatives will reduce the waste toxicity, mobility, or volume may help in assessing this criterion.

In some situations, reduction in toxicity, mobility, or volume may not be practical or even desirable. For example, unexploded munitions may be extremely dangerous to handle. In these situations, the short-term risks of treatment outweigh the potential long-term benefits.

Short-Term Effectiveness

The short-term effectiveness of each alternative will be assessed, including: the potential for fire, explosion, and exposure to hazardous substances; as well as threats associated with treatment, excavation, transportation, and disposal or containment of waste material. This criterion is important in densely populated areas and where waste characteristics are such that risks to workers or to the environment are high and special protective measures are needed.

Implementability

The implementability of each alternative will be evaluated to assess any potential impacts on the time required to implement a given remedy. Information to consider for implementability includes:

- The administrative activities needed to implement the corrective measures alternative (e.g., permits, rights of way, offsite approvals) and the length of time these activities will take

- The criteria for construction, time for implementation, and time for beneficial results

- The availability of adequate offsite treatment, storage capacity, disposal services, needed technical services, and materials

- The availability of prospective technologies for each corrective measures alternative

Cost

The CMS will consider the relative cost for each remedy. This criterion is especially useful when several technologies offer the same degree of protection to human health and the environment but vary widely in cost. The accuracy of cost estimating increases as the project moves forward from the conceptual/feasibility-type phase to an actual design, fabrication, and start-up phase. Therefore, cost estimates to be calculated in the actual CMS should be viewed as guidance and not as definitive fact in the ensuing decision-making process.

Cost estimates are generally subdivided into:

- *Direct Capital Costs:* Remedial action construction, equipment, land/site development, building and services, relocation of population, and disposal costs

- *Indirect Capital Costs:* Engineering expenses, supervision/inspection/overhead, and monitoring and testing

- *Contingency Allowances:* Varies

- *Other Indirect Expenses:* Legal fees, license/permit costs, and start-up/shake-down

- *Operation and Maintenance Costs:* Operating labor, maintenance material and labor, auxiliary materials and labor, purchased services, administration, insurance/taxes/licenses, maintenance reserve and contingency costs, and other costs

4.4 Corrective Measure Alternative Recommendation

Once corrective measures have been evaluated, the CMS report will recommend a remedial alternative based on its ability to meet the nine criteria. The recommended remedial alternative could be one remedy or a combination of remedies. Figure 4-2 is a flow chart that details the corrective measure selection process for AOC A.

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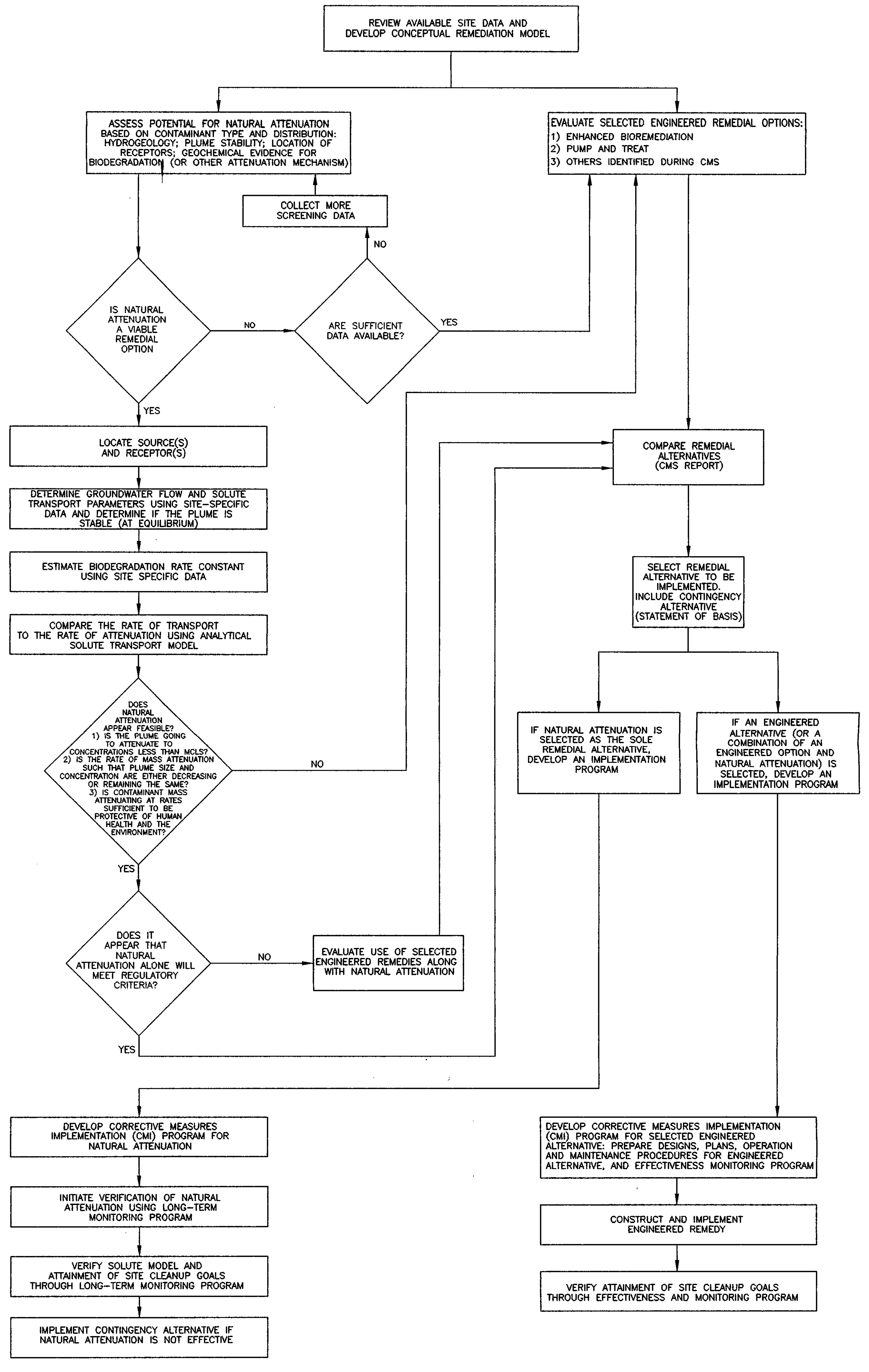

NSA MID-SOUTH
MILLINGTON, TENNESSEE

FIGURE 4-2
CORRECTIVE MEASURES
ALTERNATIVE SELECTION FLOW CHART

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5.0 PROJECT MANAGEMENT

This section outlines the proposed project management plan for the Northside fluvial deposits groundwater CMS, including project work elements, schedule, and project management responsibilities. The main goal of this effort is to achieve compliance with the HSWA portion of the Part B permit for operating a hazardous-waste storage and transfer facility.

5.1 Project Work Elements

The CMS will begin with a review of the site's characteristics, nature and extent of contamination, identification of corrective action objectives, and corrective-measures alternatives. Based on the review of these data, an in-depth analysis of alternatives will be conducted to determine the most appropriate and cost-effective corrective measures for the Northside fluvial deposits groundwater based on the nine criteria discussed in Section 4.

Results of the CMS will be presented in a CMS report, that will include the following elements:

- Introduction/Purpose
- Description of Current Conditions
- Corrective-Action Objectives
- Identification, Screening, and Development of Corrective-Measure Alternatives
- Evaluation of a Final Corrective-Measure Alternative
- Recommendation for a Final Corrective-Measure Alternative
- Public Involvement Plan

5.2 Project Schedule

This section provides a schedule for completing the CMS. Appendix C of the HSWA portion of the Part B permit contains a facility submission or compliance schedule based on task versus duration for completing the RFI/CMS. In accordance with HSWA permit Condition II.G.1, a Corrective Action Management Plan (CAMP) was prepared and submitted to the USEPA. The CAMP was originally approved by USEPA Region IV on June 29, 1993, and revised in November 1994 to address changing priorities resulting from BRAC. It has been revised since that time to reflect the current status of the CAP at NSA Mid-South.

The CAMP outlined a proposed schedule for completing the RFI and CMS implementation. The following schedule, Figure 5-1, Time Line Schedule, is a proposed schedule for the Northside fluvial groundwater CMS. This schedule is an updated version of the schedule presented in the most recent version of the CAMP (October 1997).

5.3 Project Management Responsibilities

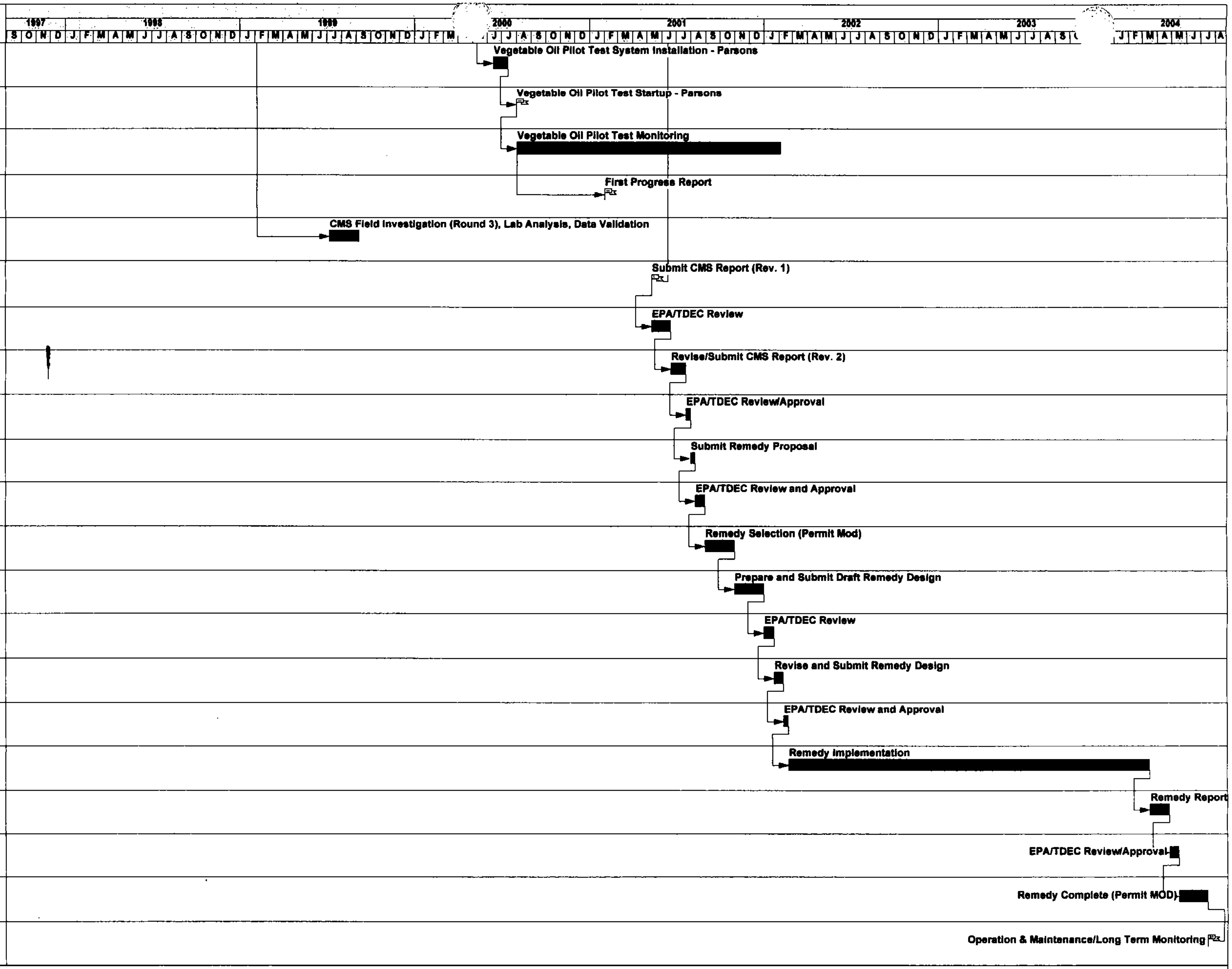
NSA Mid-South

NSA Mid-South is the RCRA permit holder for a storage facility. The Commanding Officer is responsible for all compliance with environmental laws. The Commanding Officer is Captain Diane Lofink. Other key persons at NSA Mid-South are Tonya Barker, Public Works Environmental Division Director; and Rob Williamson, IR Program Coordinator.

SOUTHNAVFACENGCOM

SOUTHNAVFACENGCOM's Engineer-in-Charge (EIC), Jim Reed, is responsible for the technical and financial management of IR Program activities at NSA Mid-South. He prepares the project statement of work; manages the project scope, schedule, and budget; and provides technical review and approval of all deliverables.

TASK	DURA	ROJECTE START	ROJECTE FINISH	
04161	30	14JUN00	14JUL00	Vegetable Oil Pilot Test System Installation - Parsons
04171	0	01AUG00		Vegetable Oil Pilot Test Startup - Parsons
04181	542	02AUG00	03FEB02	Vegetable Oil Pilot Test Monitoring
04182	0	02FEB01		First Progress Report
05181	45	06JUL99	06SEP99	CMS Field Investigation (Round 3), Lab Analysis, Data Validation
01140	0		10MAY01	Submit CMS Report (Rev. 1)
00141	40	11MAY01	19JUN01	EPA/TDEC Review
01141	30	20JUN01	20JUL01	Revise/Submit CMS Report (Rev. 2)
02141	10	21JUL01	30JUL01	EPA/TDEC Review/Approval
00142	10	31JUL01	09AUG01	Submit Remedy Proposal
00143	20	10AUG01	29AUG01	EPA/TDEC Review and Approval
00144	60	30AUG01	29OCT01	Remedy Selection (Permit Mod)
00145	60	30OCT01	30DEC01	Prepare and Submit Draft Remedy Design
00146	20	31DEC01	20JAN02	EPA/TDEC Review
00147	20	21JAN02	09FEB02	Revise and Submit Remedy Design
00148	10	10FEB02	19FEB02	EPA/TDEC Review and Approval
00149	752	20FEB02	14MAR04	Remedy Implementation
00150	40	15MAR04	23APR04	Remedy Report
00151	20	24APR04	13MAY04	EPA/TDEC Review/Approval
00152	60	14MAY04	12JUL04	Remedy Complete (Permit MOD)
00153	0		12JUL04	Operation & Maintenance/Long Term Monitoring



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Early bar
Progress bar
Summary bar
Progress point
Summary point
Start milestone point
Finish milestone point

Figure 5-1

NSA MID-SOUTH PROJECTED CMS SCHEDULE

AOC A-NORTHSIDE FLUVIAL GROUNDWATER

CORRECTIVE MEASURES STUDY
NAVAL SUPPORT ACTIVITY MID-SOUTH
MILLINGTON TN

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BRAC Cleanup Team (BCT)

The NSA Mid-South BCT is composed of a U.S. Navy BRAC Environmental Coordinator (David Porter) representing the Department of Defense, a representative from the USEPA Region IV (Brian Donaldson), and a representative from TDEC (Jim Morrison). The BCT is responsible for conducting periodic program review and for attaining consensus on decisions with federal and state regulators. This team is primarily involved in issues involving property transfer at the former naval base.

EnSafe

EnSafe is under contract to SOUTHNAVFACENGCOM to administer, plan and implement the CMS at NSA Mid-South. The following individuals will be involved in this effort:

- Task Order Manager — Lawson Anderson
- CMS Project Manager — John Stedman
- Community Relations Specialist — Keith Johns

U.S. Geological Survey

The USGS, Water Resources Division, Tennessee District, along with EnSafe, conducted the RFI on the Northside AOC A. Mr. Jack Carmichael is the USGS Project Manager and will continue to provide support to the Navy by reviewing and evaluating CMS documents.

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6.0 COMMUNITY INVOLVEMENT

Though the RCRA corrective action process typically does not require a community participation program for facilities that are experiencing RCRA-regulated assessment, investigation, and/or cleanup, it has been the policy of the U.S. Navy for NSA Mid-South to emulate a public-involvement plan comparable to what would be expected under CERCLA-mandated assessment and remediation projects.

6.1 Community Relations Plan

In response to Navy guidance, EnSafe was tasked with developing a Community Relations Plan (CRP) that details community involvement and strategy for the entire RCRA corrective action process. The CRP has been implemented to encourage open communication among NSA Mid-South; federal, state, and local regulatory agencies; interested community groups; and, individual community residents regarding environmental activities that are subsequent to NSA Mid-South remediation and closure. Community involvement has been encouraged from the beginning of the corrective action process (i.e., RFA) and will continue through the end of the corrective action process (i.e., CMI).

6.2 Benefits

Community involvement and input results in many benefits. In particular, the Restoration Advisory Board (RAB), as described in the CRP, provides a forum where applicable project information is presented to the community, and public input is actively solicited and acted upon. The implementation of any program has a greater chance for success when the community has taken an active role in the full program from start-up to alternative solution selection and implementation. It is vital to have community support during the period of solution implementation.

6.3 Public Interaction

As mentioned in previous sections of this work plan, the final product of the CMS will include a list of cleanup alternative(s) as well as the recommended alternative. The CRP requires that this list be presented to the local community through a public notice published in the newspaper, and at a public hearing. Written responses will be accepted from the public during a comment period that typically ranges from 30 to 45 days. EnSafe, in coordination with the BCT, will produce written responses to comments received during this period. Changes to the proposed cleanup alternative(s) may be made after consideration of public comments.

In addition to the public notice, hearing, and comment period, quarterly RAB meetings, which are open to the public, will act as a forum for citizen education, involvement, and input throughout the entire CMS process. Fact sheets and other educational material reporting CMS findings will be published if community interest is expressed.

7.0 REFERENCES

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Appendix A

ASTM Standards

Designation: D 5447 – 93

Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem[1]

This standard is issued under the fixed designation D 5447; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the application and subsequent documentation of a ground-water flow model to a particular site or problem. In this context, "ground-water flow model" refers to the application of a mathematical model to the solution of a site-specific ground-water flow problem.

1.2 This guide illustrates the major steps to take in developing a ground-water flow model that reproduces or simulates an aquifer system that has been studied in the field. This guide does not identify particular computer codes, software, or algorithms used in the modeling investigation.

1.3 This guide is specifically written for saturated, isothermal, ground-water flow models. The concepts are applicable to a wide range of models designed to simulate subsurface processes, such as variably saturated flow, flow in fractured media, density-dependent flow, solute transport, and multiphase transport phenomena; however, the details of these other processes are not described in this guide.

1.4 This guide is not intended to be all inclusive. Each ground-water model is unique and may require additional procedures in its development and application. All such additional analyses should be documented, however, in the model report.

1.5 This guide is one of a series of standards on ground-water model applications. Other standards have been prepared on environmental modeling, such as Practice E 978.

1.6 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

E 978 Practice for Evaluating Environmental Fate Models of Chemicals[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *application verification*—using the set of parameter values and boundary conditions from a calibrated model to approximate acceptably a second set of field data measured under similar hydrologic conditions.

3.1.1.1 *Discussion*—Application verification is to be distinguished from code verification, that refers to software testing, comparison with analytical solutions, and comparison with other similar codes to demonstrate that the code represents its mathematical foundation.

3.1.2 *boundary condition*—a mathematical expression of a state of the physical system that constrains the equations of the mathematical model.

3.1.3 *calibration (model application)*—the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulation and observations of the ground-water flow system.

3.1.4 *computer code (computer program)*—the assembly of numerical techniques, bookkeeping, and control language that represents the model from acceptance of input data and instructions to delivery of output.

3.1.5 *conceptual model*—an interpretation or working description of the characteristics and dynamics of the physical system.

3.1.6 *ground water flow model*—application of a mathematical model to represent a site-specific ground water flow system.

3.1.7 *mathematical model*—mathematical equations expressing the physical system and including simplifying assumptions. The representation of a physical system by mathematical expressions from which the behavior of the system can be deduced with known accuracy.

3.1.8 *model*—an assembly of concepts in the form of mathematical equations that portray understanding of a natural phenomenon.

3.1.9 *sensitivity (model application)*—the degree to which the model result is affected by changes in a selected model input representing hydrogeologic framework, hydraulic properties, and boundary conditions.

3.2 For definitions of other terms used in this guide, see Terminology D 653.

4. Summary of Guide

4.1 The application of a ground-water flow model ideally would follow several basic steps to achieve an acceptable representation of the physical hydrogeologic system and to document the results of the model study to the end-user, decision-maker, or regulator. These primary steps include the following:

4.1.1 Define study objectives,

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[1] This guide is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved Aug. 15, 1993. Published October 1993.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 11.04.

4.1.2 Develop a conceptual model,
4.1.3 Select a computer code,
4.1.4 Construct a ground-water flow model,
4.1.5 Calibrate model and perform sensitivity analysis,
4.1.6 Make predictive simulations,
4.1.7 Document modeling study, and
4.1.8 Perform postaudit.

4.2 These steps are designed to ascertain and document an understanding of a system, the transition from conceptual model to mathematical model, and the degree of uncertainty in the model predictions. The steps presented in this guide should generally be followed in the order they appear in the guide; however, there is often significant iteration between steps. All steps outlined in this guide are required for a model that simulates measured field conditions. In cases where the model is only used to understand a problem conceptually, not all steps are necessary. For example, if no site-specific data are available, the calibration step would be omitted.

5. Significance and Use

5.1 According to the National Research Council (**1**),[4] model applications are useful tools to:
5.1.1 Assist in problem evaluation,
5.1.2 Design remedial measures,
5.1.3 Conceptualize and study ground-water flow processes,
5.1.4 Provide additional information for decision making, and
5.1.5 Recognize limitations in data and guide collection of new data.

5.2 Ground-water models are routinely employed in making environmental resource management decisions. The model supporting these decisions must be scientifically defensible and decision-makers must be informed of the degree of uncertainty in the model predictions. This has prompted some state agencies to develop standards for ground-water modeling (**2**). This guide provides a consistent framework within which to develop, apply, and document a ground-water flow model.

5.3 This guide presents steps ideally followed whenever a ground-water flow model is applied. The ground-water flow model will be based upon a mathematical model that may use numerical, analytical, or any other appropriate technique.

5.4 This guide should be used by practicing ground-water modelers and by those wishing to provide consistency in modeling efforts performed under their direction.

5.5 Use of this guide to develop and document a ground-water flow model does not guarantee that the model is valid. This guide simply outlines the necessary steps to follow in the modeling process. For example, development of an equivalent porous media model in karst terrain may not be valid if significant ground-water flow takes place in fractures and solution channels. In this case, the modeler could follow all steps in this guide and not end up with a defensible model.

[4] The **boldface** numbers in parentheses refer to the list of references at the end of this standard.

6. Procedure

6.1 The procedure for applying a ground-water model includes the following steps: define study objectives, develop a conceptual model, select a computer code or algorithm, construct a ground-water flow model, calibrate the model and perform sensitivity analysis, make predictive simulations, document the modeling process, and perform a postaudit. These steps are generally followed in order, however, there is substantial overlap between steps, and previous steps are often revisited as new concepts are explored or as new data are obtained. The iterative modeling approach may also require the reconceptualization of the problem. An example of these feedback loops is shown in Fig. 1. These basic modeling steps are discussed below.

6.2 Definition of the study objectives is an important step in applying a ground-water flow model. The objectives aid in determining the level of detail and accuracy required in the model simulation. Complete and detailed objectives would ideally be specified prior to any modeling activities.

6.3 A conceptual model of a ground-water flow and hydrologic system is an interpretation or working description of the characteristics and dynamics of the physical hydrogeologic system. The purpose of the conceptual model is to consolidate site and regional hydrogeologic and hydrologic data into a set of assumptions and concepts that can be evaluated quantitatively. Development of the conceptual model requires the collection and analysis of hydrogeologic and hydrologic data pertinent to the aquifer system under investigation. Standard guides and practices exist that de-

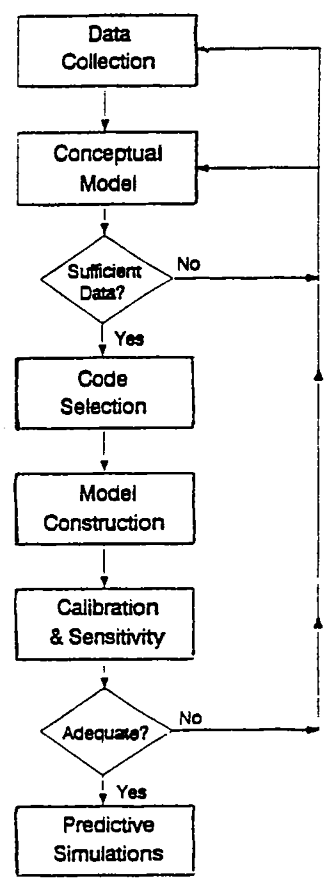

FIG. 1 Flow Chart of the Modeling Process

scribe methods for obtaining hydrogeologic and hydrologic data.

3.1 The conceptual model identifies and describes im-, ,ant aspects of the physical hydrogeologic system, including: geologic and hydrologic framework, media type (for example, fractured or porous), physical and chemical processes, hydraulic properties, and sources and sinks (water budget). These components of the conceptual model may be described either in a separate document or as a chapter within the model report. Include illustrations, where appropriate, to support the narrative, for example, contour maps, cross sections, or block diagrams, or combination thereof. Each aspect of the conceptual model is described as follows:

6.3.1.1 Geologic framework is the distribution and configuraton of aquifer and confining units. Of primary interest are the thickness, continuity, lithology, and geologic structure of those units that are relevant to the purpose of the study. The aquifer system domain, that may be composed of interconnected aquifers and confining units, often extends beyond the domain of interest. In this case, describe the aquifer system in detail within the domain of interest and at least in general elsewhere. Analysis of the geologic framework results in listings, tabulations, or maps, or combination thereof, of the thickness, extent, and properties of each relevant aquifer and confining unit.

6.3.1.2 Hydrologic framework in the conceptual model includes the physical extents of the aquifer system, hydrologic features that impact or control the ground-water flow system, analysis of ground-water flow directions, and media tvne. The conceptual model must address the degree to ı the aquifer system behaves as a porous media. If the a‚ıier system is significantly fractured or solutioned, the conceptual model must address these issues. Hydrologic framework also includes flow system boundaries that may not be physical and can change with time, such as ground-water divides. Fluid potential (head) measurements allow assessment of the rate and direction of ground-water flow. In addition, the mathematical model is typically calibrated against these values (see 6.5). Water level measurements within the ground-water system are tabulated, both spatially and temporally. This analysis of the flow system includes the assessment of vertical and horizontal gradients, delineation of ground-water divides, and mapping of flow lines.

6.3.1.3 Hydraulic properties include the transmissive and storage characteristics of the aquifer system. Specific examples of hydraulic properties include transmissivity, hydraulic conductivity, storativity, and specific yield. Hydraulic properties may be homogeneous or heterogeneous throughout the model domain. Certain properties, such as hydraulic conductivity, may also have directionality, that is, the property may be anisotropic. It is important to document field and laboratory measurements of these properties in the conceptual model to set bounds or acceptable ranges for guiding the model calibration.

6.3.1.4 Sources and sinks of water to the aquifer system impact the pattern of ground-water flow. The most common examples of sources and sinks include pumping or injection wel'- infiltration, evapotranspiration, drains, leakage across ,ing layers and flow to or from surface water bodies. Identify and describe sources and sinks within the aquifer system in the conceptual model. The description includes the rates and the temporal variability of the sources and sinks. A water budget should be developed as part of the conceptual model.

6.3.2 Provide an analysis of data deficiencies and potential sources of error with the conceptual model. The conceptual model usually contains areas of uncertainty due to the lack of field data. Identify these areas and their significance to the conceptual model evaluated with respect to project objectives. In cases where the system may be conceptualized in more than one way, these alternative conceptual models should be described and evaluated.

6.4 Computer code selection is the process of choosing the appropriate software algorithm, or other analysis technique, capable of simulating the characteristics of the physical hydrogeologic system, as identified in the conceptual model. The computer code must also be tested for the intended use and be well documented (**3–5**).

6.4.1 Other factors may also be considered in the decision-making process, such as model analyst's experience and those described below for model construction. Important aspects of the model construction process, such as dimensionality, will determine the capabilities of the computer code required for the model. Provide a narrative in the modeling report justifying the computer code selected for the model study.

6.5 Ground-water flow model construction is the process of transforming the conceptual model into a mathematical form. The ground-water flow model typically consists of two parts, the data set and the computer code. The model construction process includes building the data set utilized by the computer code. Fundamental components of the ground-water flow model include: dimensionality, discretization, boundary and initial conditions, and hydraulic properties.

6.5.1 Spatial dimensionality is determined both by the objectives of the investigation and by the nature of the ground-water flow system. For example, conceptual modeling studies may use simple one-dimensional solutions in order to test alternate conceptualizations. Two-dimensional modeling may be warranted if vertical gradients are negligible. If vertical gradients are significant or if there are several aquifers in the flow system, a two-dimensional cross section or (quasi-)three-dimensional model may be appropriate. A quasi-three-dimensional approach is one in which aquitards are not explicitly discretized but are approximated using a leakage term (**6**).

6.5.2 Temporal dimensionality is the choice between steady-state or transient flow conditions. Steady-state simulations produce average or long-term results and require that a true equilibrium case is physically possible. Transient analyses are typically performed when boundary conditions are varied through time or when study objectives require answers at more than one point in time.

6.5.3 In numerical models, spatial discretization is a critical step in the model construction process (**6**). In general, finer discretization produces a more accurate solution to the governing equations. There are practical limits to the number of nodes, however. In order to achieve acceptable results with the minimum number of nodes, the model grid may require finer discretization in areas of interest or where there are large spatial changes in aquifer parameters or hydraulic gradient. In designing a numerical model, it is advisable to locate nodes as close as possible to pumping wells, to locate model edges and hydrologic boundaries accurately, and to avoid large contrasts in adjacent nodal spacings (7).

6.5.4 Temporal discretization is the selection of the number and size of time steps for the period of transient numerical model simulations. Choose time steps or intervals to minimize errors caused by abrupt changes in boundary conditions. Generally, small time steps are used in the vicinity of such changes to improve accuracy (8). Some numerical time-stepping schemes place additional constraints on the maximum time-step size due to numerical stability.

6.5.5 Specifying the boundary conditions of the ground-water flow model means assigning a boundary type to every point along the three-dimensional boundary surface of the aquifer system and to internal sources and sinks (9). Boundary conditions fall into one of five categories: specified head or Dirichlet, specified flux or Neumann, and mixed or Cauchy boundary conditions, free surface boundary, and seepage face. It is desirable to include only natural hydrologic boundaries as boundary conditions in the model. Most numerical models, however, employ a grid that must end somewhere. Thus, it is often unavoidable to specify artificial boundaries at the edges of the model. When these grid boundaries are sufficiently remote from the area of interest, the artificial conditions on the grid boundary do not significantly impact the predictive capabilities of the model. However, the impact of artificial boundaries should always be tested and thoroughly documented in the model report.

6.5.6 Initial conditions provide a starting point for transient model calculations. In numerical ground-water flow models, initial conditions consist of hydraulic heads specified for each model node at the beginning of the simulation. Initial conditions may represent a steady-state solution obtained from the same model. Accurately specify initial conditions for transient models. Steady-state models do not require initial conditions.

6.5.7 In numerical modeling, each node or element is assigned a value for each hydraulic property required by the ground-water flow model. Other types of models, such as many analytical models, specify homogeneous property values. The most common hydraulic properties are horizontal and vertical hydraulic conductivity (or transmissivity) and storage coefficients. Hydraulic property values are assigned in the model based upon geologic and aquifer testing data. Generally, hydraulic property values are assigned in broad zones having similar geologic characteristics (10). Geostatistical techniques, such as kriging, are also commonly used to assign property values at model nodes when sufficient data are available.

6.6 Calibration of the ground-water flow model is the process of adjusting hydraulic parameters, boundary conditions, and initial conditions within reasonable ranges to obtain a match between observed and simulated potentials, flow rates, or other calibration targets. The range over which model parameters and boundary conditions may be varied is determined by data presented in the conceptual model. In the case where parameters are well characterized by field measurements, the range over which that parameter is varied in the model should be consistent with the range observed in the field. The degree of fit between model simulations and field measurements can be quantified using statistical techniques (2).

6.6.1 In practice, model calibration is frequently accomplished through trial-and-error adjustment of the model's input data to match field observations (10). Automatic inverse techniques are another type of calibration procedure (11–13). The calibration process continues until the degree of correspondence between the simulation and the physical hydrogeologic system is consistent with the objectives of the project.

6.6.2 The calibration is evaluated through analysis of residuals. A residual is the difference between the observed and simulated variable. Calibration may be viewed as a regression analysis designed to bring the mean of the residuals close to zero and to minimize the standard deviation of the residuals (10). Statistical tests and illustrations showing the distribution of residuals are presented to document the calibration. Ideally, criteria for an acceptable calibration should be established prior to starting the calibration.

6.6.3 Calibration often necessitates reconstruction of portions of the model, resulting in changes or refinements in the conceptual model. Both possibilities introduce iteration into the modeling process whereby the modeler revisits previous steps to achieve a better representation of the physical system.

6.6.4 In both trial-and-error and inverse techniques, sensitivity analysis plays a key role in the calibration process by identifying those parameters that are most important to model reliability. Sensitivity analysis is used extensively in inverse techniques to make adjustments in model parameter values.

6.6.5 Calibration of a ground-water flow model to a single set of field measurements does not guarantee a unique solution. In order to reduce the problem of nonuniqueness, the model calculations may be compared to another set of field observations that represent a different set of boundary conditions or stresses. This process is referred to in the ground-water modeling literature as either validation (1) or verification (14, 15). The term verification is adopted in this guide. In model verification, the calibrated model is used to simulate a different set of aquifer stresses for which field measurements have been made. The model results are then compared to the field measurements to assess the degree of correspondence. If the comparison is not favorable, additional calibration or data collection is required. Successful verification of the ground-water flow model results in a higher degree of confidence in model predictions. A calibrated but unverified model may still be used to perform predictive simulations when coupled with a careful sensitivity analysis (15).

6.7 Sensitivity analysis is a quantitative method of determining the effect of parameter variation on model results. The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions (6). It is a means to identify the model inputs that have the most influence on model calibration and predictions (1). Perform sensitivity analysis to provide users with an understanding of the level of confidence in model results and to identify data deficiencies (16).

6.7.1 Sensitivity analysis is performed during model calibration and during predictive analyses. Model sensitivity provides a means of determining the key parameters and boundary conditions to be adjusted during model calibration. Sensitivity analysis is used in conjunction with predictive simulations to assess the effect of parameter uncertainty on model results.

6.7.2 Sensitivity of a model parameter is often expressed as the relative rate of change of a selected model calculation with respect to that parameter (17). If a small change in the input parameter or boundary condition causes a significant change in the output, the model is sensitive to that parameter or boundary condition.

6.8 Application of the ground-water flow model to a particular site or problem often includes predictive simulations. Predictive simulations are the analyses of scenarios defined as part of the study objectives. Document predictive simulations with appropriate illustrations as necessary in the model report.

6.8.1 Boundary conditions are often selected during model construction based upon existing or past ground-water flow conditions. Boundary conditions used in the calibrated model may not be appropriate for all predictive simulations (18). If the model simulations result in unusually large hydrologic stresses or if new stresses are placed in proximity to model boundaries, evaluate the sensitivity of the predictions to the boundary conditions. This may produce additional iteration in the modeling process.

6.9 In cases where the ground-water flow model has been used for predictive purposes, a postaudit may be performed to determine the accuracy of the predictions. While model calibration and verification demonstrate that the model accurately simulate past behavior of the system, the postaudit tests whether the model can predict future system behavior (15). Postaudits are normally performed several years after submittal of the modeling report and are therefore documented in a separate report.

7. Report

7.1 The purpose of the model report is to communicate findings, to document the procedures and assumptions inherent in the study, and to provide detailed information for peer review. The report should be a complete document allowing reviewers and decision makers to formulate their own opinion as to the credibility of the model. The report should be detailed enough that an independent modeler could duplicate the model results. The model report should describe all aspects of the modeling study outlined in this guide. An example table of contents for a modeling report is presented in Appendix X1.

8. Keywords

8.1 computer model; ground-water; simulation

APPENDIX

(Nonmandatory Information)

1.0 Introduction
- 1.1 General Setting
- 1.2 Study Objectives

2.0 Conceptual Model
- 2.1 Aquifer System Framework
- 2.2 Ground-Water Flow System
- 2.3 Hydrologic Boundaries
- 2.4 Hydraulic Properties
- 2.5 Sources and Sinks
- 2.6 Water Budget

3.0 Computer Code
- 3.1 Code Selection
- 3.2 Code Description

4.0 Ground-Water Flow Model Construction
- 4.1 Model Grid
- 4.2 Hydraulic Parameters
- 4.3 Boundary Conditions
- 4.4 Selection of Calibration Targets

5.0 Calibration
- 5.1 Residual Analysis
- 5.2 Sensitivity Analysis
- 5.3 Model Verification

6.0 Predictive Simulations

7.0 Summary and Conclusions
- 7.1 Model Assumptions and Limitations
- 7.2 Model Predictions
- 7.3 Recommendations

8.0 References

Appendices: Model Input Files

FIG. X1.1 Example Table of Contents of Ground-Water Flow Model Report

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Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information[1]

This standard is issued under the fixed designation D 5490; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers techniques that should be used to compare the results of ground-water flow model simulations to measured field data as a part of the process of calibrating a ground-water model. This comparison produces quantitative and qualitative measures of the degree of correspondence between the simulation and site-specific information related to the physical hydrogeologic system.

1.2 During the process of calibration of a ground-water flow model, each simulation is compared to site-specific information such as measured water levels or flow rates. The degree of correspondence between the simulation and the physical hydrogeologic system can then be compared to that for previous simulations to ascertain the success of previous calibration efforts and to identify potentially beneficial directions for further calibration efforts.

1.3 By necessity, all knowledge of a site is derived from observations. This guide does not address the adequacy of any set of observations for characterizing a site.

1.4 This guide does not establish criteria for successful calibration, nor does it describe techniques for establishing such criteria, nor does it describe techniques for achieving successful calibration.

1.5 This guide is written for comparing the results of numerical ground-water flow models with observed site-specific information. However, these techniques could be applied to other types of ground-water related models, such as analytical models, multiphase flow models, non-continuum (karst or fracture flow) models, or mass transport models.

1.6 This guide is one of a series of guides on ground-water modeling codes (software) and their applications. Other standards have been prepared on environmental modeling, such as Practice E 978.

1.7 The values stated in SI units are to be regarded as the standard.

1.8 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

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E 978 Practice for Evaluating Environmental Fate Models of Chemicals[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *application verification*—using the set of parameter values and boundary conditions from a calibrated model to approximate acceptably a second set of field data measured under similar hydrologic conditions.

3.1.1.1 *Discussion*—Application verification is to be distinguished from code verification which refers to software testing, comparison with analytical solutions, and comparison with other similar codes to demonstrate that the code represents its mathematical foundation.

3.1.2 *calibration*—the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the ground-water flow system.

3.1.3 *censored data*—knowledge that the value of a variable in the physical hydrogeologic system is less than or greater than a certain value, without knowing the exact value.

3.1.3.1 *Discussion*—For example, if a well is dry, then the potentiometric head at that place and time must be less than the elevation of the screened interval of the well although its specific value is unknown.

3.1.4 *conceptual model*—an interpretation or working description of the characteristics and dynamics of the physical system.

3.1.5 *ground-water flow model*—an application of a mathematical model to represent a ground-water flow system.

3.1.6 *hydrologic condition*—a set of ground-water inflows or outflows, boundary conditions, and hydraulic properties that cause potentiometric heads to adopt a distinct pattern.

3.1.7 *residual*—the difference between the computed and observed values of a variable at a specific time and location.

3.1.8 *simulation*—in ground-water flow modeling, one complete execution of a ground-water modeling computer program, including input and output.

3.1.8.1 *Discussion*—For the purposes of this guide, a simulation refers to an individual modeling run. However, simulation is sometimes also used broadly to refer to the process of modeling in general.

[1] This guide is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved Nov. 15, 1993. Published January 1994.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 11.04.

3.2 For definitions of other terms used in this guide, see ninology D 653.

4. Summary of Guide

4.1 Quantitative and qualitative comparisons are both essential. Both should be used to evaluate the degree of correspondence between a ground-water flow model simulation and site-specific information.

4.2 Quantitative techniques for comparing a simulation with site-specific information include:

4.2.1 Calculation of residuals between simulated and measured potentiometric heads and calculation of statistics regarding the residuals. Censored data resulting from detection of dry or flowing observation wells, reflecting information that the head is less than or greater than a certain value without knowing the exact value, should also be used.

4.2.2 Detection of correlations among residuals. Spatial and temporal correlations among residuals should be investigated. Correlations between residuals and potentiometric heads can be detected using a scattergram.

4.2.3 Calculation of flow-related residuals. Model results should be compared to flow data, such as water budgets, surface water flow rates, flowing well discharges, vertical gradients, and contaminant plume trajectories.

4.3 Qualitative considerations for comparing a simulation with site-specific information include:

4.3.1 Comparison of general flow features. Simulations should reproduce qualitative features in the pattern of ground-water contours, including ground-water flow direc-, mounds or depressions (closed contours), or indica-s of surface water discharge or recharge (cusps in the contours).

4.3.2 Assessment of the number of distinct hydrologic conditions to which the model has been successfully calibrated. It is usually better to calibrate to multiple scenarios, if the scenarios are truly distinct.

4.3.3 Assessment of the reasonableness or justifiability of the input aquifer hydrologic properties given the aquifer materials which are being modeled. Modeled aquifer hydrologic properties should fall within realistic ranges for the physical hydrogeologic system, as defined during conceptual model development.

5. Significance and Use

5.1 During the process of calibration of a ground-water flow model, each simulation is compared to site-specific information to ascertain the success of previous calibration efforts and to identify potentially beneficial directions for further calibration efforts. Procedures described herein provide guidance for making comparisons between ground-water flow model simulations and measured field data.

5.2 This guide is not meant to be an inflexible description of techniques comparing simulations with measured data; other techniques may be applied as appropriate and, after due consideration, some of the techniques herein may be omitted, altered, or enhanced.

uantitative Techniques

6.1 Quantitative techniques for comparing simulations to site-specific information include calculating potentiometric head residuals, assessing correlation among head residuals, and calculating flow residuals.

6.1.1 *Potentiometric Head Residuals*—Calculate the residuals (differences) between the computed heads and the measured heads:

$$r_i = h_i - H_i \tag{1}$$

where:

r_i = the residual,
H_i = the measured head at point i,
h_i = the computed head at the approximate location where H_i was measured.

If the residual is positive, then the computed head was too high; if negative, the computed head was too low. Residuals cannot be calculated from censored data.

NOTE 1—For drawdown models, residuals can be calculated from computed and measured drawdowns rather than heads.

NOTE 2—Comparisons should be made between point potentiometric heads rather than ground-water contours, because contours are the result of interpretation of data points and are not considered basic data in and of themselves.[4] Instead, the ground-water contours are considered to reflect features of the conceptual model of the site. The ground-water flow model should be true to the essential features of the conceptual model and not to their representation.

NOTE 3—It is desirable to set up the model so that it calculates heads at the times and locations where they were measured, but this is not always possible or practical. In cases where the location of a monitoring well does not correspond exactly to one of the nodes where heads are computed in the simulation, the residual may be adjusted (for example, computed heads may be interpolated, extrapolated, scaled, or otherwise transformed) for use in calculating statistics. Adjustments may also be necessary when the times of measurements do not correspond exactly with the times when heads are calculated in transient simulations; when many observed heads are clustered near a single node; where the hydraulic gradient changes significantly from node to node; or when observed head data is affected by tidal fluctuations or proximity to a specified head boundary.

6.1.2 *Residual Statistics*—Calculate the maximum and minimum residuals, a residual mean, and a second-order statistic, as described in the following sections.

6.1.2.1 *Maximum and Minimum Residuals*—The maximum residual is the residual that is closest to positive infinity. The minimum residual is the residual closest to negative infinity. Of two simulations, the one with the maximum and minimum residuals closest to zero has a better degree of correspondence, with regard to this criterion.

NOTE 4—When multiple hydrologic conditions are being modeled as separate steady-state simulations, the maximum and minimum residual can be calculated for the residuals in each, or for all residuals in all scenarios, as appropriate. This note also applies to the residual mean (see 6.1.2.2) and second-order statistics of the residuals (see 6.1.2.4).

6.1.2.2 *Residual Mean*—Calculate the residual mean as the arithmetic mean of the residuals computed from a given simulation:

$$R = \frac{\sum_{i=1}^{n} r_i}{n} \tag{2}$$

where:

[4] Cooley, R. L., and Naff, R. L., "Regression Modeling of Ground-Water Flow," *USGS Techniques of Water Resources Investigations*, Book 3, Chapter B4, 1990.

R = the residual mean and
n = the number of residuals.

Of two simulations, the one with the residual mean closest to zero has a better degree of correspondence, with regard to this criterion (assuming there is no correlation among residuals).

6.1.2.3 If desired, the individual residuals can be weighted to account for differing degrees of confidence in the measured heads. In this case, the residual mean becomes the weighted residual mean:

$$R = \frac{\sum_{i=1}^{n} w_i r_i}{n \sum_{i=1}^{n} w_i} \tag{3}$$

where w_i is the weighting factor for the residual at point i. The weighting factors can be based on the modeler's judgment or statistical measures of the variability in the water level measurements. A higher weighting factor should be used for a measurement with a high degree of confidence than for one with a low degree of confidence.

NOTE 5—It is possible that large positive and negative residuals could cancel, resulting in a small residual mean. For this reason, the residual mean should never be considered alone, but rather always in conjunction with the other quantitative and qualitative comparisons.

6.1.2.4 *Second-Order Statistics*—Second-order statistics give measures of the amount of spread of the residuals about the residual mean. The most common second-order statistic is the standard deviation of residuals:

$$s = \left\{ \frac{\sum_{i=1}^{n} (r_i - R)^2}{n - 1} \right\}^{1/2} \tag{4}$$

where s is the standard deviation of residuals. Smaller values of the standard deviation indicate better degrees of correspondence than larger values.

6.1.2.5 If weighting is used, calculate the weighted standard deviation:

$$s = \left\{ \frac{\sum_{i=1}^{n} w_i (r_i - R)^2}{(n - 1) \sum_{i=1}^{n} w_i} \right\}^{1/2} \tag{5}$$

NOTE 6—Other norms of the residuals are less common but may be revealing in certain cases.[5,6] For example, the mean of the absolute values of the residuals can give information similar to that of the standard deviation of residuals.

NOTE 7—In calculating the standard deviation of residuals, advanced statistical techniques incorporating information from censored data could be used. However, the effort would usually not be justified because the standard deviation of residuals is only one of many indicators involved in comparing a simulation with measured data, and such a refinement in one indicator is unlikely to alter the overall assessment of the degree of correspondence.

6.1.3 *Correlation Among Residuals*—Spatial or temporal correlation among residuals can indicate systematic trends or bias in the model. Correlations among residuals can be identified through listings, scattergrams, and spatial or temporal plots. Of two simulations, the one with less correlation among residuals has a better degree of correspondence, with regard to this criterion.

6.1.3.1 *Listings*—List residuals by well or piezometer, including the measured and computed values to detect spatial or temporal trends. Figures X1.1 and X1.2 present example listings of residuals.

6.1.3.2 *Scattergram*—Use a scattergram of computed versus measured heads to detect trends in deviations. The scattergram is produced with measured heads on the abscissa (horizontal axis) and computed heads on the ordinate (vertical axis). One point is plotted on this graph for each pair. If the points line up along a line with zero intercept and 45° angle, then there has been a perfect match. Usually, there will be some scatter about this line, hence the name of the plot. A simulation with a small degree of scatter about this line has a better correspondence with the physical hydrogeologic system than a simulation with a large degree of scatter. In addition, plotted points in any area of the scattergram should not all be grouped above or below the line. Figures X1.3 and X1.4 show sample scattergrams.

6.1.3.3 *Spatial Correlation*—Plot residuals in plan or section to identify spatial trends in residuals. In this plot, the residuals, including their sign, are plotted on a site map or cross section. If possible or appropriate, the residuals can also be contoured. Apparent trends or spatial correlations in the residuals may indicate a need to refine aquifer parameters or boundary conditions, or even to reevaluate the conceptual model (for example, add spatial dimensions or physical processes). For example, if all of the residuals in the vicinity of a no-flow boundary are positive, then the recharge may need to be reduced or the hydraulic conductivity increased. Figure X1.5 presents an example of a contour plot of residuals in plan view. Figure X1.6 presents an example of a plot of residuals in cross section.

6.1.3.4 *Temporal Correlation*—For transient simulations, plot residuals at a single point versus time to identify temporal trends. Temporal correlations in residuals can indicate the need to refine input aquifer storage properties or initial conditions. Figure X1.7 presents a typical plot of residuals versus time.

6.1.4 *Flow-Related Residuals*—Often, information relating to ground-water velocities is available for a site. Examples include water budgets, surface water flow rates, flowing well discharges, vertical gradients, and contaminant plume trajectories (ground-water flow paths). All such quantities are dependent on the hydraulic gradient (the spatial derivative of the potentiometric head). Therefore, they relate to the overall structure of the pattern of potentiometric heads and provide information not available from point head measurements. For each such datum available, calculate the residual between its computed and measured values. If possible and appropriate, calculate statistics on these residuals and assess their correlations, in the manner described in 5.1.1 and 5.1.2 for potentiometric head residuals.

6.1.4.1 *Water Budgets and Mass Balance*—For elements of the water budget for a site which are calculated (as opposed to specified in the model input) (for example, base flow to a stream), compare the computed and the measured

[5] Ghassemi, F., Jakeman, A. J., and Thomas, G. A., "Ground-Water Modeling for Salinity Management: An Australian Case Study," *Ground Water*, Vol 27, No. 3, 1989, pp. 384–392.

[6] Konikow, L. F., *Calibration of Ground-Water Models, Proceedings of the Specialty Conference on Verification of Mathematical and Physical Models in Hydraulic Engineering*, ASCE, College Park, MD, Aug. 9–11, 1978, pp. 87–93.

(or estimated) values. In addition, check the computed mass balance for the simulation by comparing the sum of all inflows to the sum of all outflows and changes in storage. Differences of more than a few percent in the mass balance indicate possible numerical problems and may invalidate simulation results.

6.1.4.2 *Vertical Gradients*—In some models, it may be more important to accurately represent the difference in heads above and below a confining layer, rather than to reproduce the heads themselves. In such a case, it may be acceptable to tolerate a correlation between the head residuals above and below the layer if the residual in the vertical gradient is minimized.

6.1.4.3 *Ground-Water Flow Paths*—In some models, it may be more important to reproduce the pattern of streamlines in the ground-water flow system rather than to reproduce the heads themselves (for example, when a flow model is to be used for input of velocities into a contaminant transport model). In this case, as with the case of vertical gradients in 6.1.4.2 it may be acceptable to tolerate some correlation in head residuals if the ground-water velocity (magnitude and direction) residuals are minimized.

7. Qualitative Considerations

7.1 *General Flow Features*—One criterion for evaluating the degree of correspondence between a ground-water flow model simulation and the physical hydrogeologic system is whether or not essential qualitative features of the potentiometric surface are reflected in the model. The overall pattern of flow directions and temporal variations in the model should correspond with those at the site. For example:

7.1.1 If there is a mound or depression in the potentiometric surface at the site, then the modeled contours should also indicate a mound or depression in approximately the same area.

7.1.2 If measured heads indicate or imply cusps in the ground-water contours at a stream, then these features should also appear in contours of modeled heads.

7.2 *Hydrologic Conditions*—Identify the different hydrologic conditions that are represented by the available data sets. Choose one data set from each hydrologic condition to use for calibration. Use the remaining sets for verification.

7.2.1 *Uniqueness (Distinct Hydrologic Conditions)*—The number of distinct hydrologic conditions that a given set of input aquifer hydrologic properties is capable of representing is an important qualitative measure of the performance of a model. It is usually better to calibrate to multiple conditions, if the conditions are truly distinct. Different hydrologic conditions include, but are not limited to, high and low recharge; conditions before and after pumping or installation of a cutoff wall or cap; and high and low tides, flood stages for adjoining surface waters, or installation of drains. By matching different hydrologic conditions, the uniqueness problem is addressed, because one set of heads can be matched with the proper ratio of ground-water flow rates to hydraulic conductivities; whereas, when the flow rates are changed, representing a different condition, the range of acceptable hydraulic conductivities becomes much more limited.

7.2.2 *Verification (Similar Hydrologic Conditions)*—When piezometric head data are available for two times of similar hydrologic conditions, only one of those conditions should be included in the calibration data sets because they are not distinct. However, the other data set can be used for model verification. In the verification process, the modeled piezometric heads representing the hydrologic condition in question are compared, not to the calibration data set, but to the verification data set. The resulting degree of correspondence can be taken as an indicator or heuristic measure of the ability of the model to represent new hydrologic conditions within the range of those to which the model was calibrated.

NOTE 8—When only one data set is available, it is inadvisable to artificially split it into separate "calibration" and "verification" data sets. It is usually more important to calibrate to piezometric head data spanning as much of the modeled domain as possible.

NOTE 9—Some researchers maintain that the word "verification" implies a higher degree of confidence than is warranted.[7] Used here, the verification process only provides a method for estimating confidence intervals on model predictions.

7.3 *Input Aquifer Hydraulic Properties*—A good correspondence between a ground-water flow model simulation and site-specific information, in terms of quantitative measures, may sometimes be achieved using unrealistic aquifer hydraulic properties. This is one reason why emphasis is placed on the ability to reproduce multiple distinct hydrologic stress scenarios. Thus, a qualitative check on the degree of correspondence between a simulation and the physical hydrogeologic system should include an assessment of the likely ranges of hydraulic properties for the physical hydrogeologic system at the scale of the model or model cells and whether the properties used in the model lie within those ranges.

8. Report

8.1 When a report for a ground-water flow model application is produced, it should include a description of the above comparison tests which were performed, the rationale for selecting or omitting comparison tests, and the results of those comparison tests.

9. Keywords

9.1 calibration; computer; ground water; modeling

[7] Konikow, L. F., and Bredehoeft, J. D., "Ground-Water Models Cannot Be Validated," *Adv. Wat. Res.* Vol 15, 1992, pp. 75–83.

APPENDIX

(Nonmandatory Information)

X1. EXAMPLES

X1.1 Figures X1.1 and X1.2 present sample listings of residuals, as described in 6.1.3.1. These listings tabulate the residuals for simulations of two hydrologic conditions with the same model. Note that some of the wells do not have measurements for both simulations. Simulated heads for these wells are still reported as an aid to detecting temporal trends in the heads for different aquifer stresses. Some censored water level data were available for this site. For these data, the table merely indicates whether or not the simulation is consistent with the censored data.

X1.2 Figures X1.3 and X1.4 show sample scattergrams, as described in 6.1.3.2. The scattergram on Fig. X1.3 indicates a good match between modeled and measured potentiometric heads because there is little or no pattern between positive and negative residuals and because the magnitude of the residuals is small compared to the total change in potentiometric head across the site. The residuals shown on the scattergram on Fig. X1.4 have the same maximum, minimum, mean, and standard deviation as those shown on Fig. X1.3, but show a pattern of positive

Example Site
Stress scenario #1
Simulation #24-1

Residuals:
Number of residuals : 18
Maximum residual (m): 2.62 at MW-31
Minimum residual (m): -2.51 at MW-5
Residual mean (m): 0.15
Standard deviation of residuals (m): 1.49

Censored Data:
Number of inequalities met : 1
Number of inequalities not met : 1

WELL	MEASURED HEAD (M)	SIMULATED HEAD (M)	RESIDUAL (M)
MW-1	100.79	101.57	0.78
MW-2	104.52	103.14	-1.38
MW-3	103.07	101.26	-1.81
MW-4	<101.10	100.97	YES
MW-5	106.82	104.31	-2.51
MW-6	99.94	100.39	0.45
MW-7	101.43	102.84	1.41
MW-8	89.26	89.43	0.17
MW-9	89.34	87.53	-1.81
MW-10	<97.97	98.02	NO
MW-11		96.94	
MW-12		88.60	
MW-13		91.85	
MW-14		77.57	
MW-15		103.04	
MW-16		103.12	
MW-17	95.44	97.84	2.40
MW-18		104.80	
MW-19		95.32	
MW-20		103.14	
MW-21		94.31	
MW-22	101.02	99.54	-1.48
MW-23	70.79	71.69	0.90
MW-24		99.09	
MW-25		100.80	
MW-26	98.26	98.23	-0.03
MW-27	87.44	89.03	1.59
MW-28		98.79	
MW-29	83.30	83.14	-0.16
MW-30	82.99	85.03	2.04
MW-31	95.51	98.13	2.62
MW-32	97.63	97.80	0.17
MW-33	134.02	133.46	-0.56

FIG. X1.1 Example Listings of Residuals

Example Site
Stress scenario #2
Simulation #24-2

Residuals:
Number of residuals : 22
Maximum residual (m): 2.30 at MW-24
Minimum residual (m): -2.15 at MW-20
Residual mean (m): 0.15
Standard deviation of residuals (m): 1.22

Censored Data:
Number of inequalities met : 2
Number of inequalities not met : 0

WELL	MEASURED HEAD (m)	SIMULATED HEAD (m)	RESIDUAL (m)
MW-1	101.72	101.11	-0.61
MW-2	98.43	98.77	0.34
MW-3	100.04	100.80	0.76
MW-4	<101.10	100.57	YES
MW-5	102.95	104.45	1.50
MW-6	100.00	100.66	0.66
MW-7	101.56	102.80	1.24
MW-8	92.24	90.42	-1.82
MW-9	90.34	88.77	-1.57
MW-10	<97.97	96.88	YES
MW-11		97.69	
MW-12		90.01	
MW-13		93.43	
MW-14		80.27	
MW-15		103.58	
MW-16		103.32	
MW-17	96.33	98.62	2.29
MW-18		105.73	
MW-19		96.65	
MW-20	105.25	103.10	-2.15
MW-21	96.10	95.11	-0.99
MW-22		99.63	
MW-23	74.01	75.21	1.20
MW-24	96.66	98.96	2.30
MW-25	98.04	98.71	0.67
MW-26	97.39	98.21	0.82
MW-27	90.11	90.48	0.37
MW-28	100.23	98.76	-1.47
MW-29	84.92	84.98	0.06
MW-30	86.15	86.88	0.73
MW-31	97.87	97.38	-0.49
MW-32	97.31	97.17	-0.14
MW-33	134.43	133.96	-0.47

FIG. X1.2 Example Listings of Residuals

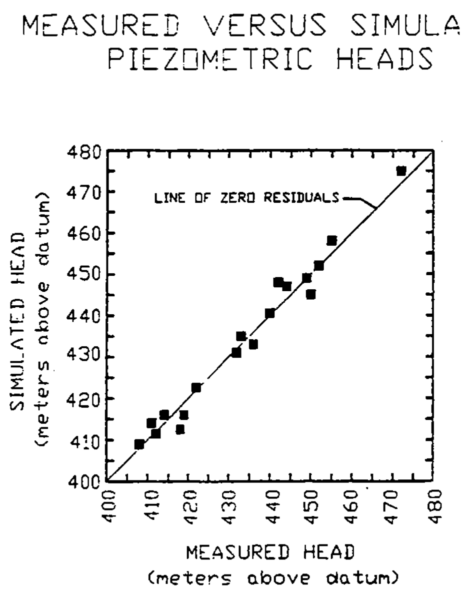

FIG. X1.3 Sample Scattergram

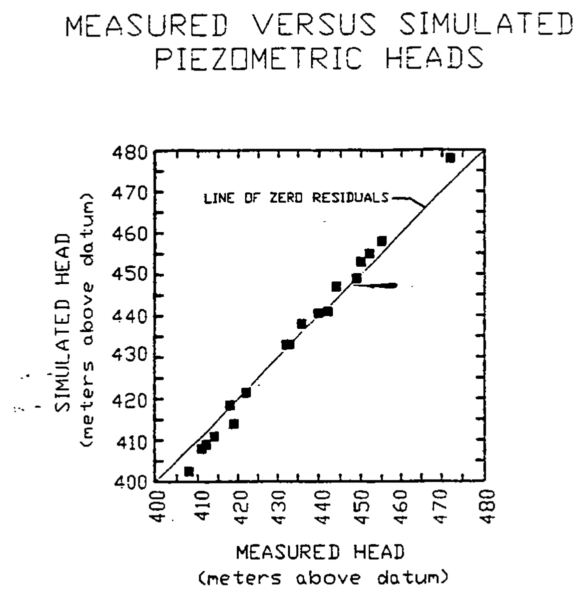

FIG. X1.4 Sample Scattergram

residuals upgradient and negative residuals downgradient. However, even though the statistical comparisons would indicate a good degree of correspondence, this model may overestimate seepage velocities because the simulated hydraulic gradient is higher than the measured hydraulic gradient. Therefore this model may need to be improved if the heads are to be input into a mass transport model.

X1.3 Figures X1.5 and X1.6 show sample plots of residuals in plan and cross-section, as described in 6.1.3.3. In Fig. X1.5, there are sufficient data to contour the residuals. The contours indicate potentially significant correlations between residuals in the northwest and southwest corners of the model. Along the river, the residuals appear to be uncorrelated. In Fig. X1.6, residuals were not contoured due to their sparseness and apparent lack of correlation.

X1.4 Figure X1.7 shows a sample plot of measured and simulated potentiometric heads and their residuals for one well in a transient simulation, as described in 6.1.3.4. The upper graph shows the measured potentiometric head at the well as measured using a pressure transducer connected to a data logger. In addition, simulated potentiometric heads for the same time period are also shown. The lower graph shows the residuals. This example shows how residuals can appear uncorrelated in a model that does not represent essential characteristics of the physical hydrogeologic system, in this case by not reproducing the correct number of maxima and minima.

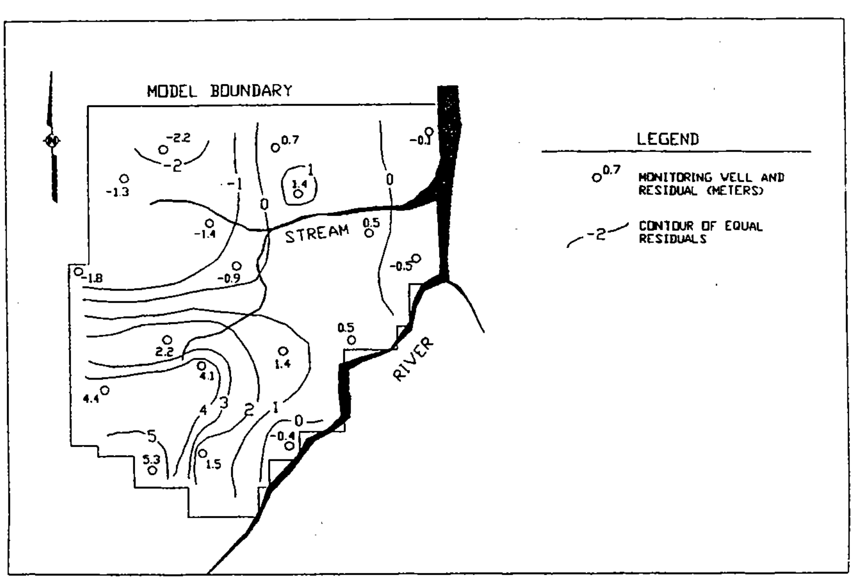

FIG. X1.5 Sample Contours of Residuals Plan View

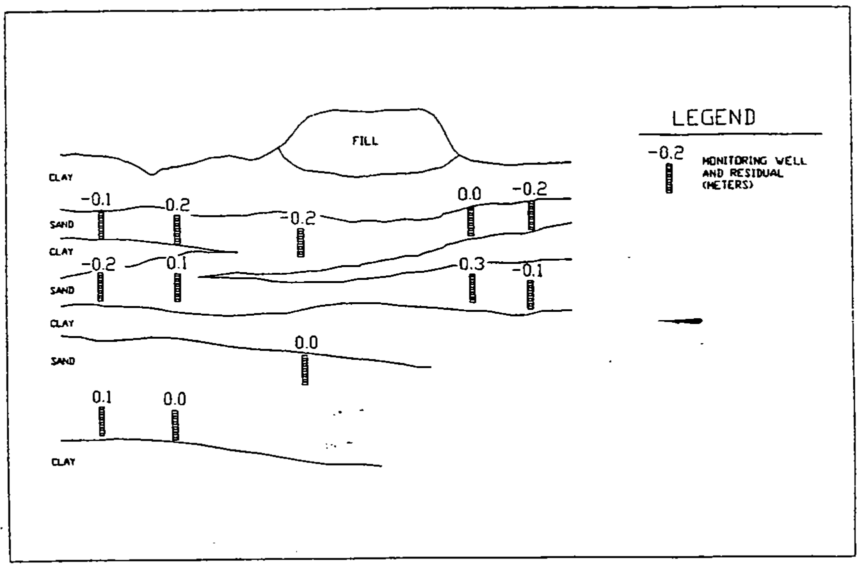

FIG. X1.6 Sample Plot of Residuals Section View

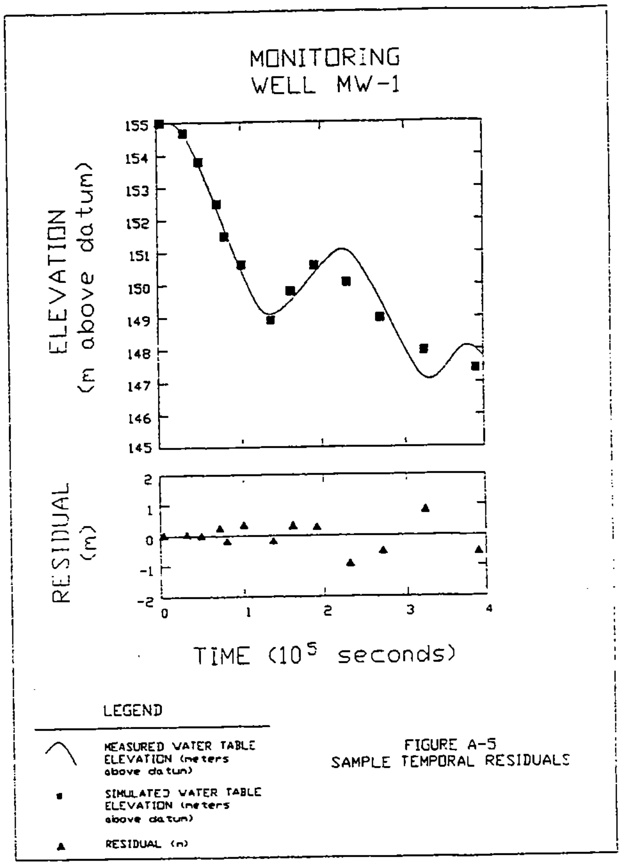

FIG. X1.7 Sample Temporal Residuals

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Designation: D 5609 – 94

Standard Guide for Defining Boundary Conditions in Ground-Water Flow Modeling[1]

This standard is issued under the fixed designation D 5609; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the specification of appropriate boundary conditions that are an essential part of conceptualizing and modeling ground-water systems. This guide describes techniques that can be used in defining boundary conditions and their appropriate application for modeling saturated ground-water flow model simulations.

1.2 This guide is one of a series of standards on ground-water flow model applications. Defining boundary conditions is a step in the design and construction of a model that is treated generally in Guide D 5447.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 5447 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *boundary*—geometrical configuration of the surface enclosing the model domain.

3.1.3 *boundary condition*—a mathematical expression of the state of the physical system that constrains the equations of the mathematical model.

3.1.4 *conceptual model*—a simplified representation of the hydrogeologic setting and the response of the flow system to stress.

3.1.5 *flux*—the volume of fluid crossing a unit cross-sectional surface area per unit time.

3.1.6 *ground-water flow model*—an application of a mathematical model to the solution of a ground-water flow problem.

3.1.7 *hydraulic conductivity—(field aquifer tests),* the volume of water at the existing kinematic viscosity that will move in a unit time under unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.8 *hydrologic condition*—a set of ground-water inflows or outflows, boundary conditions, and hydraulic properties that cause potentiometric heads to adopt a distinct pattern.

3.1.9 *simulation*—one complete execution of the computer program, including input and output.

3.1.10 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.11 *unconfined aquifer*—an aquifer that has a water table.

3.1.12 For definitions of other terms used in this test method, see Terminology D 653.

4. Significance and Use

4.1 Accurate definition of boundary conditions is an essential part of conceptualizing and modeling ground-water flow systems. This guide describes the properties of the most common boundary conditions encountered in ground-water systems and discusses major aspects of their definition and application in ground-water models. It also discusses the significance and specification of boundary conditions for some field situations and some common errors in specifying boundary conditions in ground-water models.

5. Types of Boundaries

5.1 The flow of ground water is described in the general case by partial differential equations. Quantitative modeling of a ground-water system entails the solution of those equations subject to site-specific boundary conditions.

5.2 *Types of Modeled Boundary Conditions*—Flow model boundary conditions can be classified as specified head or Dirichlet, specified flux or Neumann, a combination of specified head and flux, or Cauchy, free surface boundary, and seepage-face. Each of these types of boundaries and some of their variations are discussed below.

5.2.1 *Specified Head, or Dirichlet, Boundary Type*—A specified head boundary is one in which the head can be specified as a function of position and time over a part of the boundary surface of the ground-water system. A boundary of specified head may be the general type of specified head boundary in which the head may vary with time or position over the surface of the boundary, or both, or the constant-head boundary in which the head is constant in time, but head may differ in position, over the surface of the boundary. These two types of specified head boundaries are discussed below.

[1] This guide is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Investigations.

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[2] *Annual Book of ASTM Standards,* Vol 04.08.

[3] *Annual Book of ASTM Standards,* Vol 04.09.

5.2.1.1 *General Specified-Head Boundary*—The general type of specified-head boundary condition occurs wherever head can be specified as a function of position and time over a part of the boundary surface of a ground-water system. An example of the simplest type might be an aquifer that is exposed along the bottom of a large stream whose stage is independent of ground-water seepage. As one moves upstream or downstream, the head changes in relation to the slope of the stream channel and the head varies with time as a function of stream flow. Heads along the stream bed are specified according to circumstances external to the ground-water system and maintain these specified values throughout the problem solution, regardless of changes within the ground-water system.

5.2.1.2 *Constant-Head Boundary*—A constant head boundary is boundary in which the aquifer system coincides with a surface of unchanging head through time. An example is an aquifer that is bordered by a lake in which the surface-water stage is constant over all points of the boundary in time and position or an aquifer that is bordered by a stream of constant flow that is unchanging in head with time but differs in head with position.

5.2.2 *Specified Flux or Neumann Boundary Type*—A specified flux boundary is one for which the flux across the boundary surface can be specified as a function of position and time. In the simplest type of specified-flux boundary, the flux across a given part of the boundary surface is considered uniform in space and constant with time. In a more general case, the flux might be constant with time but specified as a function of position. In the most general case, flux is specified as a function of time as well as position. In all cases of specified flux boundaries, the flux is specified according to circumstances external to the ground-water flow system and the specified flux values are maintained throughout the problem solution regardless of changes within the ground-water flow system.

5.2.2.1 *No Flow or Streamline Boundary*—The no-flow or streamline boundary is a special case of the specified flux boundary. A streamline is a curve that is tangent to the flow-velocity vector at every point along its length; thus no flow crosses a streamline. An example of a no-flow boundary is an impermeable boundary. Natural earth materials are never impermeable. However, they may sometimes be regarded as effectively impermeable for modeling purposes if the hydraulic conductivities of the adjacent materials differ by orders of magnitude. Ground-water divides are normal to streamlines and are also no-flow boundaries. However, the ground-water divide does not intrinsically correspond to physical or hydraulic properties of the aquifer. The position of a ground-water divide is a function of the response of the aquifer system to hydrologic conditions and may be subject to change with changing conditions. The use of ground-water divides as model boundaries may produce invalid results.

5.2.3 *Head Dependent Flux, or Cauchy Type*—In some situations, flux across a part of the boundary surface changes in response to changes in head within the aquifer adjacent to the boundary. In these situations, the flux is a specified function of that head and varies during problem solution as head varies.

NOTE 1—An example of this type of boundary is the upper surface of an aquifer overlain by a confining bed that is in turn overlain by a body of surface water. In this example, as in most head-dependent boundary situations, a practical limit exists beyond which changes in head cease to cause a change in flux. In this example, the limit will be reached where the head within the aquifer falls below the top of the aquifer so that the aquifer is no longer confined at that point, but is under an unconfined or water-table condition, while the confining bed above remains saturated. Under these conditions, the bottom of the confining bed becomes locally a seepage face. Thus as the head in the aquifer is drawn down further, the hydraulic gradient does not increase and the flux through the confining bed remains constant. In this hypothetical case, the flux through the confining bed increases linearly as the head in the aquifer declines until the head reaches the level of the base of the confining bed after which the flux remains constant. Another example of a head dependent boundary with a similar behavior is evapotranspiration from the water table, where the flux from the water table is often modeled as decreasing linearly with depth to water and becomes zero where the water table reaches some specified "cutoff" depth.

5.2.4 *Free-Surface Boundary Type*—A free-surface boundary is a moveable boundary where the head is equal to the elevation of the boundary. The most common free-surface boundary is the water table, which is the boundary surface between the saturated flow field and the atmosphere (capillary zone not considered). An important characteristic of this boundary is that its position is not fixed; that is its position may rise and fall with time. In some problems, for example, flow through an earth dam, the position of the free surface is not known before but must be found as part of the problem solution.

5.2.4.1 Another example of a free surface boundary is the transition between freshwater and underlying seawater in a coastal aquifer. If diffusion is neglected and the salty ground water seaward of the interface is assumed to be static, the freshwater-saltwater transition zone can be treated as a sharp interface and can be taken as the bounding stream surface (no-flow) boundary of the fresh ground-water flow system. Under these conditions, the freshwater head at points on the interface varies only with the elevation and the freshwater head at any point on this idealized stream-surface boundary is thus a linear function of the elevation head of that point.

5.2.5 *Seepage-Face Boundary Type*—A surface of seepage is a boundary between the saturated flow field and the atmosphere along which ground water discharges, either by evaporation or movement "downhill" along the land surface as a thin film in response to the force of gravity. The location of this type of boundary is generally fixed, but its length is dependent upon other system boundaries. A seepage surface is always associated with a free surface boundary. Seepage faces are commonly neglected in models of large aquifer systems because their effect is often insignificant at a regional scale of problem definition. However, in problems defined over a smaller area, which require more accurate system definition, they must be considered.

6. Procedure

6.1 The definition of boundary conditions of a model is a part of the application of a model to a site-specific problem (see Guide D 5447). The steps in boundary definition may be stated as follows:

6.1.1 Identification of the physical boundaries of the flow system boundaries,

6.1.2 Formulation of the mathematical representation of the boundaries,

6.1.3 Examination and sensitivity testing of boundary conditions that change when the system is under stress, that is, stress-dependent boundaries, and

6.1.4 Revision and final formulation of the initial model boundary representation.

6.1.5 Further examination, testing, and refinement of the model boundaries is a part of the verification and validation process of the application of each model and is discussed in Guide D 5447.

6.2 *Boundary Identification*—Identify as accurately as possible the physical boundaries of the flow system. The three-dimensional bounding surfaces of the flow system must be defined even if the model is to be represented by a two-dimensional model. Even if the lateral boundaries are distant from the region of primary interest, it is important to understand the location and hydraulic conditions on the boundaries of the flow system.

6.2.1 *Ground-Water Divides*—Ground-water divides have been chosen as boundaries by some modelers because they can be described as stream lines and can be considered as no flow boundaries. However, the locations of ground-water divides depend upon hydrologic conditions in the sense that they can move or disappear in response to stress on the system. For these reasons, ground-water divides are not physical boundaries of the flow system.[4] Their representation as no-flow boundaries can sometimes be justified if the objective of the simulation is to gain an understanding of natural flow without applied stress or if the changed conditions used for simulation can be shown, for example, by sensitivity analysis, to have a negligible effect on the position of the boundary.

6.2.2 *Water Table*—The water table is an important boundary in many ground-water flow systems and various ways of treating the water table may be appropriate in different ground-water models. The position of the water table is not fixed and the water table boundary may act as a source or sink of water. Some of these ways of treating the water table are discussed below.

6.2.2.1 The position of the water table is not fixed, but it may be appropriate to treat the water table as a constant-head boundary in a steady-state simulation where the flow distribution in an unstressed model is simulated.

6.2.2.2 The water table may be represented as a free-surface boundary with recharge, in which case, the water table is neither a potential nor a stream surface.

6.2.2.3 The water table may be represented as a free surface boundary with discharge in which discharge is by evapotranspiration as a function of depth to water. The boundary in this case is a head-dependent flux boundary.

6.2.2.4 A sloping water table may be represented as a flow surface, that is, a locus of flow lines, where accretion is zero.

6.2.2.5 The water table may be a surface at which accretion, the net rate of gain or loss normal to the aquifer surface, is a function of time and location.

6.3 *Model Representation*—Formulate the model representation for the bounding surfaces of the flow system. Define the hydraulic conditions on the boundaries: specified head, specified flux, head-dependent flux, free surface boundary or seepage face.

6.4 *Stress Dependency*—Examine the stress-dependence of each boundary. Perform sensitivity analysis of boundaries to determine their stress dependency and to determine if natural boundaries are compatible with the representation in the model.

6.4.1 For example, a specified head boundary assumes the head is independent of the stress in the model. If the stress applied to the real system will affect the head on the boundary, the boundary is stress-dependent and modeling the boundary as a specified head boundary is not a valid representation of the boundary. Likewise, specified flux boundaries assume the flux to or from the model is independent of the stress in the model and if flux to or from the model is dependent upon head in the model, the boundary is a stress-dependent boundary and requires such recognition in representing the boundary.

6.4.1.1 Consider the physical boundary in relation to system stress to be applied during simulation. The model representation of a system boundary may be a function of the nature and magnitude of stress applied to the system during model simulation. Consider, for example, a small to medium-sized stream, which may function as a specified head boundary if the stress does not induce flow to or from the stream of sufficient magnitude to significantly affect the stream stage. If, however, the stress is so large as to cause a part of the stream to dry up, then the stream can no longer be treated as a specified head boundary. The stream may need to be modeled as a flux dependent head boundary.

6.4.1.2 If the boundary conditions are stress dependent, the model cannot be considered a general, all-purpose tool for investigating any stress on the system because it will give valid results only when the stresses do not impact the boundary. The study of a new stress on the same model may require the reformulation of the representation of boundaries of the model and sensitivity tests on the model boundary representation.

6.4.1.3 Stress-dependency is of primary concern wherever the model boundaries differ from the natural system boundaries. For example, model boundaries that may differ from physical boundaries of the flow system include natural boundaries that may extend beyond the boundaries of the model. Prepare a careful justification to show that the proposed boundary is appropriate and will not cause the model solution to differ substantially from the response that would occur in the real system.

6.5 The results of stress-dependency tests should be documented with regard to stress conditions and the magnitude of impact on stress-dependent boundaries.

6.6 *Revise Model Boundary Representation*—Based on the sensitivity testing, revise model boundary representations and document the ranges of stress for which the boundaries are designed.

7. Report

7.1 Completely document the boundary definition of the models. Such documentation will be a part of the overall documentation of the model. Include the following items pertaining to the formulation of model boundaries in the model report:

[4] Franke, O. L., Reilly, T. E., and Bennett, G. D., "Definition of Boundary and Initial Conditions in the Analysis of Ground-Water Flow Systems—An Introduction," *Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter B5, 1987.*

7.1.1 Describe the natural physical boundaries of the ·del and the processes operating at the boundaries, and

1.2 Describe the formulation of the model boundaries, the stress dependency of the boundaries and the model representation of each boundary. Evaluate the sensitivity analysis of the boundaries and state the conditions of stress over which the modeled boundary conditions are appropriate.

8. Keywords

8.1 aquifers; boundary condition; ground-water model

Standard Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application[1]

This standard is issued under the fixed designation D 5611; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers techniques that should be used to conduct a sensitivity analysis for a ground-water flow model. The sensitivity analysis results in quantitative relationships between model results and the input hydraulic properties or boundary conditions of the aquifers.

1.2 After a ground-water flow model has been calibrated, a sensitivity analysis may be performed. Examination of the sensitivity of calibration residuals and model conclusions to model inputs is a method for assessing the adequacy of the model with respect to its intended function.

1.3 After a model has been calibrated, a modeler may vary the value of some aspect of the conditions applying solely to the prediction simulations in order to satisfy some design criteria. For example, the number and locations of proposed pumping wells may be varied in order to minimize the required discharge. Insofar as these aspects are controllable, variation of these parameters is part of an optimization procedure, and, for the purposes of this guide, would not be considered to be a sensitivity analysis. On the other hand, estimates of future conditions that are not controllable, such as the recharge during a postulated drought of unknown duration and severity, would be considered as candidates for a sensitivity analysis.

1.4 This guide presents the simplest acceptable techniques for conducting a sensitivity analysis. Other techniques have been developed by researchers and could be used in lieu of the techniques in this guide.

1.5 This guide is written for performing sensitivity analyses for ground-water flow models. However, these techniques could be applied to other types of ground-water related models, such as analytical models, multi-phase flow models, non-continuum (karst or fracture flow) models, or mass transport models.

1.6 This guide is one of a series on ground-water modeling codes (software) and their applications, such as Guide D 5447 and Guide D 5490. Other standards have been prepared on environmental modeling, such as Practice E 978.

1.7 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 5447 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem[3]

D 5490 Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information[3]

E 978 Practice for Evaluating Environmental Fate Models of Chemicals[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *boundary condition*—a mathematical expression of a state of the physical system that constrains the equations of the mathematical model.

3.1.2 *calibration*—the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the ground-water flow system.

3.1.2.1 *Discussion*—During calibration, a modeler may vary the value of a model input to determine the value which produces the best degree of correspondence between the simulation and the physical hydrogeologic system. This process is sometimes called sensitivity analysis but for the purposes of this guide, sensitivity analysis begins only after calibration is complete.

3.1.3 *calibration targets*—measured, observed, calculated, or estimated hydraulic heads or ground-water flow rates that a model must reproduce, at least approximately, to be considered calibrated.

3.1.4 *ground-water flow model*—an application of a mathematical model to represent a ground-water flow system.

3.1.4.1 *Discussion*—This term refers specifically to modeling of ground-water hydraulics, and not to contaminant transport or other ground-water processes.

3.1.5 *hydraulic properties*—intensive properties of soil and rock that govern the transmission (that is, hydraulic conductivity, transmissivity, and leakance) and storage (that is, specific storage, storativity, and specific yield) of water.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

[4] *Annual Book of ASTM Standards*, Vol 11.04.

3.1.6 *residual*—the difference between the computed and observed values of a variable at a specific time and location.

3.1.7 *sensitivity*—the variation in the value of one or more output variables (such as hydraulic heads) or quantities calculated from the output variables (such as ground-water flow rates) due to variability or uncertainty in one or more inputs to a ground-water flow model (such as hydraulic properties or boundary conditions).

3.1.8 *sensitivity analysis*—a quantitative evaluation of the impact of variability or uncertainty in model inputs on the degree of calibration of a model and on its results or conclusions.[5]

3.1.8.1 *Discussion*—Anderson and Woessner[5] use "calibration sensitivity analysis" for assessing the effect of uncertainty on the calibrated model and "prediction sensitivity analysis" for assessing the effect of uncertainty on the prediction. The definition of sensitivity analysis for the purposes of this guide combines these concepts, because only by simultaneously evaluating the effects on the model's calibration and predictions can any particular level of sensitivity be considered significant or insignificant.

3.1.9 *simulation*—one complete execution of a ground-water modeling computer program, including input and output.

3.2 For definitions of other terms used in this guide, see Terminology D 653.

4. Significance and Use

4.1 After a model has been calibrated and used to draw conclusions about a physical hydrogeologic system (for example, estimating the capture zone of a proposed extraction well), a sensitivity analysis can be performed to identify which model inputs have the most impact on the degree of calibration and on the conclusions of the modeling analysis.

4.2 If variations in some model inputs result in insignificant changes in the degree of calibration but cause significantly different conclusions, then the mere fact of having used a calibrated model does not mean that the conclusions of the modeling study are valid.

4.3 This guide is not meant to be an inflexible description of techniques of performing a sensitivity analysis; other techniques may be applied as appropriate and, after due consideration, some of the techniques herein may be omitted, altered, or enhanced.

5. Sensitivity Analysis

5.1 The first step for performing a sensitivity analysis is to identify which model inputs should be varied. Then, for each input: execute calibration and prediction simulations with the value of the input varied over a specified range; graph calibration residuals and model predictions as functions of the value of the input; and determine the type of sensitivity that the model has with respect to the input.

5.2 *Identification of Inputs to be Varied:*

5.2.1 Identify model inputs that are likely to affect computed hydraulic heads and ground-water flow rates at the times and locations where similar measured quantities exist, and thereby affect calibration residuals. Also, identify model inputs that are likely to affect the computed hydraulic heads upon which the model's conclusions are based in the predictive simulations.

5.2.2 Usually, changing the value of an input at a single node or element of a model will not significantly affect any results. Therefore, it is important to assemble model inputs into meaningful groups for variation. For example, consider an unconfined aquifer that discharges into a river. If the river is represented in a finite-difference model by 14 nodes, then varying the conductance of the river-bottom sediments in only one of the nodes will not significantly affect computed flow into the river or computed hydraulic heads. Unless there are compelling reasons otherwise, the conductance in all river nodes should be varied as a unit.

5.2.3 Coordinated changes in model inputs are changes made to more than one type of input at a time. In ground-water flow models, some coordinated changes in input values (for example, hydraulic conductivity and recharge) can have little effect on calibration but large effects on prediction. If the model was not calibrated to multiple hydrologic conditions, sensitivity analysis of coordinated changes can identify potential non-uniqueness of the calibrated input data sets.

5.3 *Execution of Simulations:*

5.3.1 For each input (or group of inputs) to be varied, decide upon the range over which to vary the values. Some input values should be varied geometrically while others should be varied arithmetically. The type of variation for each input and the range over which it is varied are based on the modeler's judgment, with the goal of finding a Type IV

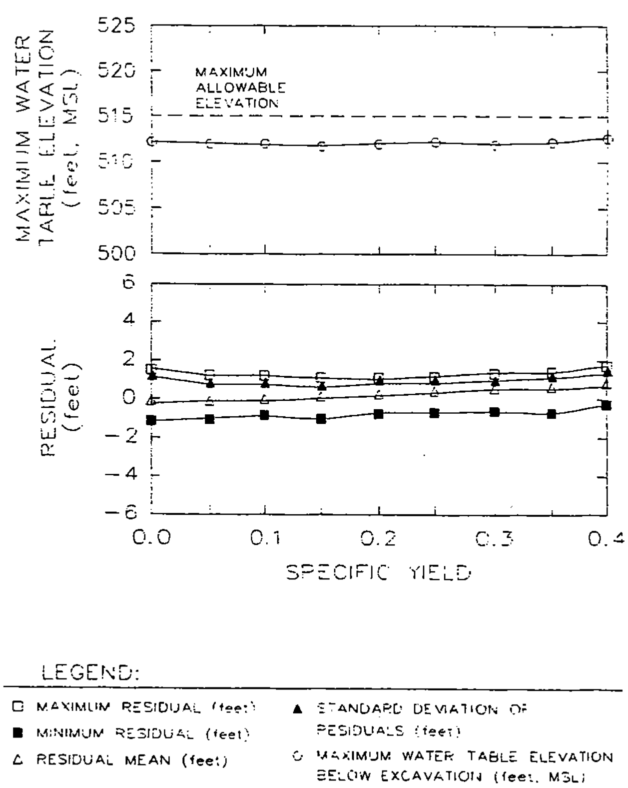

FIG. 1 Sample Graph of Sensitivity Analysis, Type I Sensitivity

[5] Anderson, Mary P., and Woessner, William W., *Applied Groundwater Modeling—Simulation of Flow and Advective Transport*, Academic Press, Inc., San Diego, 1992.

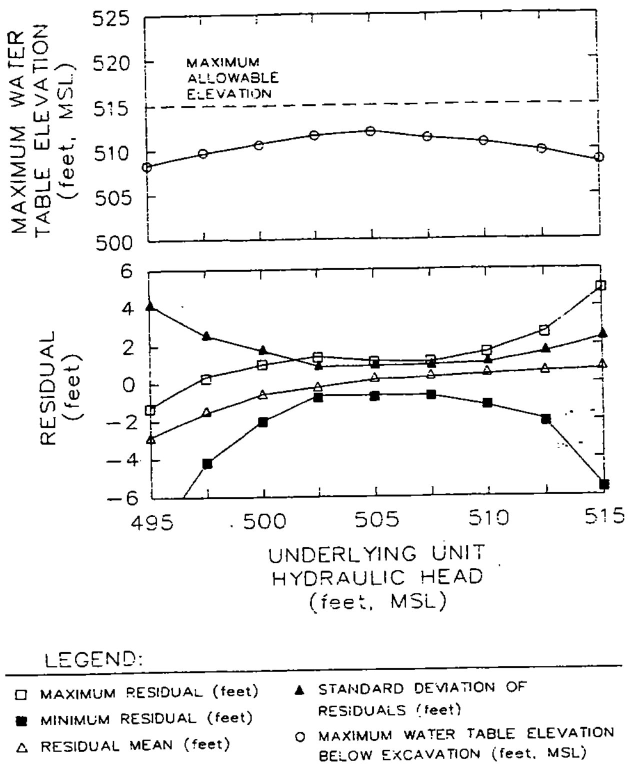

FIG. X1.2 Sample Graph of Sensitivity Analysis, Type II Sensitivity

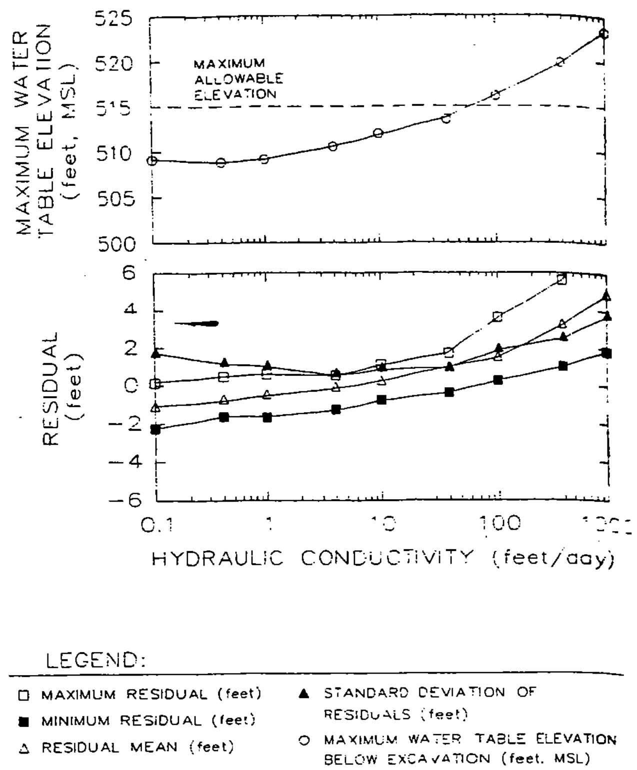

FIG. X1.3 Sample Graph of Sensitivity Analysis, Type III Sensitivity

sensitivity (see 5.5.1.4) if it exists.

NOTE 2—If the value of a model input (or group of inputs) was measured in the field, then that input need only be varied with the range of the error of the measurement.

5.3.2 For each value of each group of inputs, rerun the calibration and prediction runs of the model with the new value in place of the calibrated value. Calculate the calibration residuals (or residual statistics, or both) that result as a consequence of using the new value. Determine the effect of the new value on the model's conclusions based on using the new value in the prediction simulations.

5.4 *Graphing Results:*

5.4.1 For each input (or group of inputs), prepare a graph of the effect of variation of that parameter upon calibration residuals and the model's conclusions. Figures 1 through 4 show sample graphs of the results of sensitivity analyses.

5.4.2 Rather than display the effect on every residual, it may be more appropriate to display the effect on residual statistics such as maximum residual, minimum residual, residual mean, and standard deviation of residuals (see Guide D 5490).

5.4.3 In some cases, it may be more illustrative to present contours of head change as a result of variation of input values. In transient simulations, graphs of head change versus time may be presented.

5.4.4 Other types of graphs not mentioned here may be more appropriate in some circumstances.

5.5 *Determination of the Type of Sensitivity:*

5.5.1 For each input (or group of inputs), determine the type of sensitivity of the model to that input. There are four types of sensitivity, Types I through IV, depending on whether the changes to the calibration residuals and model's conclusions are significant or insignificant. The four types of sensitivity are described in the following sections and summarized on Fig. 5.

NOTE 3—Whether a given change in the calibration residuals or residual statistics is considered significant or insignificant is a matter of judgment. On the other hand, changes in the model's conclusions are usually able to be characterized objectively. For example, if a model is used to design an excavation dewatering system, then the computed water table is either below or above the bottom of the proposed excavation.

5.5.1.1 *Type I Sensitivity*—When variation of an input causes insignificant changes in the calibration residuals as well as the model's conclusions, then that model has a Type I sensitivity to the input. Figure 1 shows an example of Type I sensitivity. Type I sensitivity is of no concern because regardless of the value of the input, the conclusion will remain the same.

5.5.1.2 *Type II Sensitivity*—When variation of an input causes significant changes in the calibration residuals but insignificant changes in the model's conclusions, then that model has a Type II sensitivity to the input. Figure 2 shows an example of Type II sensitivity. Type II sensitivity is of no concern because regardless of the value of the input, the conclusion will remain the same.

5.5.1.3 *Type III Sensitivity*—When variation of an input causes significant changes to both the calibration residuals and the model's conclusions, then that model has a Type III sensitivity to the input. Figure 3 shows an example of Type

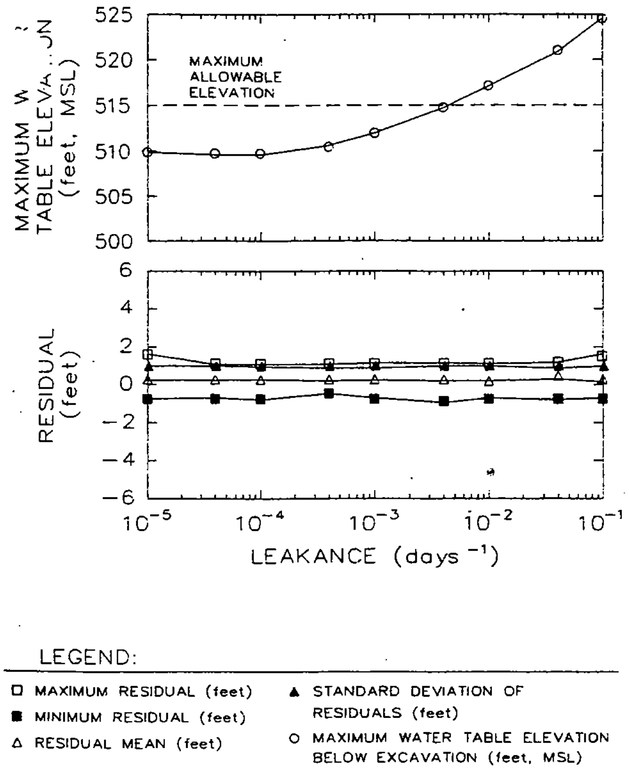

FIG. 4 Sample Graph of Sensitivity Analysis, Type IV Sensitivity

h. .nsitivity. Type III sensitivity is of no concern because, even though the model's conclusions change as a result of variation of the input, the parameters used in those simulations cause the model to become uncalibrated. Therefore, the calibration process eliminates those values from being considered to be realistic.

5.5.1.4 *Type IV Sensitivity*—If, for some value of the input that is being varied, the model's conclusions are changed but the change in calibration residuals is insignificant, then the model has a Type IV sensitivity to that input. Figure 4 shows an example of Type IV sensitivity. Type IV sensitivity can invalidate model results because over the range of that parameter in which the model can be considered calibrated, the conclusions of the model change. A Type IV sensitivity generally requires additional data collection to decrease the range of possible values of the parameter.

5.5.2 Some input parameters (for example, the hydraulic conductivity of a proposed cutoff wall) are used only in the prediction simulations. In such a case, the sensitivity is automatically either Type III or IV, depending on the significance of the changes in the model's conclusions. If Type IV, supporting documentation for the value of the parameter used in the prediction simulations is necessary (but not necessarily sufficient) to justify the conclusions of the model.

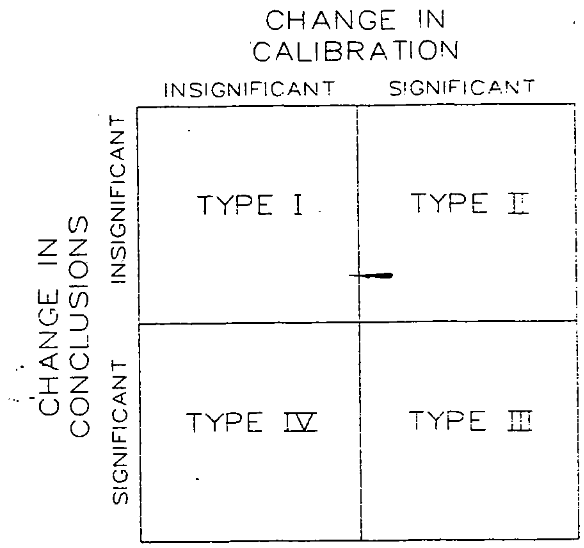

FIG. X1.5 Summary of Sensitivity Types

6. Report

6.1 If a sensitivity analysis is not performed, the report should state why a sensitivity analysis was not needed. If a sensitivity analysis is performed, the report should state which model inputs were varied and which computed outputs were examined. The report should justify the selection of model inputs and computed outputs in terms of the modeling objective.

6.2 For each model input that was varied, the report should present a graph showing the changes in residuals (or residual statistics) and the computed outputs with respect to changes in the model input. The report should either state that none of the analyses had a Type IV result, or else identify which analyses had Type IV results.

7. Keywords

7.1 calibration; computer; ground water; modeling; sensitivity

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE SENSITIVITY GRAPHS

1 Consider a hypothetical ground-water flow model t. .o design an excavation dewatering system. The bottom of the excavation will be at an elevation of 520 ft (158.5 m) above mean sea level (MSL), and the water table must be at least 5 feet below the excavation floor, or no more than 515 ft (157.0 m) MSL. Four parameters are selected for sensitivity analysis: the specific yield of a sand unit, hydraulic conductivity of the sand unit, the leakance of a clay unit, and

the hydraulic head in an underlying silty sand unit. Figures 1 through 4 show sample graphs of the results of sensitivity analyses performed on these parameters.

X1.1.1 Figure 1 shows the results of a sensitivity analysis performed on the specific yield of the sand unit. The calibrated value was 0.2. As the specific yield was varied from 0.0 to 0.4, neither the calibration residuals nor the model conclusion varied significantly as a result of variation in the specific yield. Therefore the model has Type I sensitivity to specific yield.

X1.1.2 Figure 2 shows the results of a sensitivity analysis performed on the hydraulic head of an underlying unit. The calibrated value was 505 ft (153.9 m) MSL. As the hydraulic head was varied from 495 to 515 ft (150.9 to 157.0 m), MSL, the residuals statistics degraded significantly. However, although the maximum water table elevation below the excavation changed, the conclusion of the model (that the excavation would stay dry) did not change. Therefore the model has Type II sensitivity to the hydraulic head in the underlying unit.

X1.1.3 Figure 3 shows the results of a sensitivity analysis performed on the hydraulic conductivity of the sand un The calibrated value of the hydraulic conductivity was 10 (3.05 m/d) per day and it was varied from 0.1 to 1000 (0.03 to 304.8 m/d) per day. As the hydraulic conductivi exceeded 50 feet per day, the water table below the excav tion increased to above 515 ft (157.0 m), MSL. However, t calibration residuals also increased, so that the model cou no longer be considered calibrated. Therefore, the fact th the model's conclusion changed (that is, for some values the parameter, the excavation was no longer dry) is unimpo tant. This is an example of Type III sensitivity.

X1.1.4 Figure 4 shows the results of a sensitivity analy performed on the leakance of an underlying clay unit. T calibrated value was 10^{-3} days^{-1}. As the leakance was vari from 10^{-5} to 10^{-1} days^{-1}, the calibration residuals remain practically constant. However, at the higher leakances, t excavation was not dewatered. Therefore, the conclusion the model varied significantly while the calibration did n This is a Type IV sensitivity, and it invalidates the use of t model for design of the excavation dewatering system un the actual value of the leakance can be determined.

X1.2 Figure 5 shows a summary of the four types sensitivity and the conditions under which they occur.

Appendix B

Technology Screening Tables

Table B-1
Additional Treatment Technologies Screening Matrix

Technology	A	B	C	D	E	F	G	H	I	J	K	L	M
Soil, Sediment, and Sludge													
Biodegradation	Full	■	None	No	■	■	■	Δ	■	Δ	Δ	○	2
Bioventing	Full	■	None	No	■	■	■	Δ	□	■	○	■	1
White Rot Fungus	Pilot	Δ	None	No	Δ	Δ	Δ	Δ	■	Δ	Δ	○	2
Pneumatic Fracturing (enhancement)	Pilot	Δ	None	Yes	○	○	○	○	○	■	NA	■	1
Soil Flushing	Pilot	■	Liquid	No	■	○	○	■	Δ	○	Δ	□	2
Soil Vapor Extraction (in situ)	Full	■	Liquid	No	■	○	■	Δ	Δ	■	○	■	2
In Situ Solidification/Stabilization	Full	■	Solid	No	Δ	○	Δ	■	Δ	■	■	■	3
Thermally Enhanced SVE	Full	○	Liquid	No	○	■	○	Δ	Δ	○	■	○	4
In Situ Vitrification	Pilot	Δ	Liquid	No	○	○	○	■	Δ	Δ	■	Δ	4
Composting	Full	■	None	No	■	○	■	Δ	■	■	○	■	1
Controlled Solid Phase Bio. Treatment	Full	■	None	No	■	○	■	Δ	■	■	○	■	1
Landfarming	Full	■	None	No	■	○	■	Δ	○	■	Δ	■	1
Slurry Phase Bio. Treatment	Full	○	None	No	■	○	■	Δ	■	○	○	○	4
Chemical Reduction/Oxidation	Full	■	Solid	Yes	○	○	○	■	Δ	■	■	○	1
Dehalogenation	Full	Δ	Vapor	No	○	■	Δ	Δ	Δ	□	□	□	5
Dehalogenation (Glycolate)	Full	○	Liquid	No	○	■	Δ	Δ	Δ	Δ	Δ	Δ	4
Soil Washing	Full	○	Solid, Liquid	Yes	○	■	■	■	■	○	■	○	4
Solid Vapor Extraction (ex situ)	Full	■	Liquid	No	■	○	○	Δ	Δ	■	○	■	1
Ex Situ Solidification/Stabilization	Full	■	Solid	No	Δ	○	Δ	■	Δ	■	■	■	3

Notes:

A = Development Status
B = Availability
C = Residuals Produced
D = Treatment Train
E = Volatile Organic Compounds
F = Semivolatile Organic Compounds
UV = Ultraviolet
G = Fuels

H = Inorganics
I = Explosives
J = System Reliability/
J = Maintainability
K = Cleanup Time
L = Overall Cost
POTW = Public Owned Treatment Works

M = Cost Driver
1 = Neither
2 = Operations & Maintenance
3 = Capital
4 = Both
5 = Inadequate Data

■ = Better
○ = Average
Δ = Worse
□ = Inadequate Data
NA = Not Applicable
NPDES = National Pollutant DischargeElimination System

This table is based on EnSafe experience and U.S. Environmental Protection Agency's *Remediation Technology Screening Matrix and Reference Guide*, EPA/542/B-94/013 October 1994.

Table B-1
Additional Treatment Technologies Screening Matrix

Technology	A	B	C	D	E	F	G	H	I	J	K	L	M
Soil, Sediment, and Sludge (cont'd)													
Solvent Extraction (chemical extraction)	Full	○	Liquid	Yes	○	■	○	Δ	■	○	Δ	Δ	4
High-temperature Thermal Desorption	Full	■	Liquid	Yes	○	■	○	Δ	Δ	○	■	○	4
Hot Gas Decontamination	Pilot	○	None	No	Δ	Δ	Δ	Δ	■	■	■	■	4
Incineration	Full	■	Liquid Solid	No	○	■	■	Δ	■	○	■	Δ	4
Low-temperature Thermal Desorption	Full	■	Liquid	Yes	■	○	■	Δ	■	○	■	■	4
Open Burn/Open Detonation	Full	■	Solid	No	Δ	Δ	Δ	Δ	■	■	■	■	4
Pyrolysis	Full	Δ	Liquid Solid	No	○	■	○	Δ	□	□	■	Δ	4
Ex Situ Vitrification	Full	○	Liquid	No	○	○	○	■	Δ	○	○	Δ	4
Excavation, Retrieval, and Offsite Disposal	NA	■	NA	No	○	○	○	○	○	■	■	Δ	1
Natural Attenuation	NA	■	None	No	■	■	■	Δ	Δ	■	Δ	■	1
No Action	Full	■	All	No	○	○	○	○	○	Δ	Δ	Δ	1
Filter Press	Full	■	Liquid	No	Δ	Δ	Δ	■	Δ	■	○	■	4
Groundwater, Surface Water, and Leachate													
Cometabolic Treatment	Pilot	Δ	None	No	■	■	○	Δ	○	Δ	○	○	2
Nitrate Enhancement	Pilot	Δ	None	No	■	■	■	Δ	○	○	○	■	1
Oxygen Enhancement with Air Sparging	Full	■	None	No	■	■	■	Δ	○	■	○	■	1

Notes:

A = Development Status	H = Inorganics	M = Cost Driver	■ = Better
B = Availability	I = Explosives	1 = Neither	○ = Average
C = Residuals Produced	J = System Reliability/	2 = Operations &	Δ = Worse
D = Treatment Train	J = Maintainability	Maintenance	□ = Inadequate Data
E = Volatile Organic Compounds	K = Cleanup Time	3 = Capital	NA = Not Applicable
F = Semivolatile Organic Compounds	L = Overall Cost	4 = Both	NPDES = National Pollutant DischargeElimination System
UV = Ultraviolet	POTW = Public Owned Treatment Works	5 = Inadequate Data	
G = Fuels			

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Table B-1
Additional Treatment Technologies Screening Matrix

Technology	A	B	C	D	E	F	G	H	I	J	K	L	M
Groundwater, Surface Water, and Leachate (cont'd)													
Oxygen Enhancement with H_2O_2	Full	■	None	No	■	■	■	Δ	○	Δ	○	○	2
Air Sparging	Full	■	Vapor	Yes	■	Δ	■	Δ	Δ	■	■	■	1
Directional Wells (enhancement)	Full	Δ	NA	Yes	○	○	○	○	○	○	■	□	1
Dual-phase Extraction	Full	■	Liquid Vapor	Yes	■	Δ	■	Δ	Δ	○	○	○	2
Free-product Recovery	Full	■	Liquid	No	Δ	■	■	Δ	Δ	○	■	■	1
Hot Water or Steam Flushing/Stripping	Pilot	○	Liquid Vapor	Yes	○	■	■	Δ	Δ	Δ	■	○	3
Hydrofracturing (enhancement)	Pilot	□	None	Yes	○	○	○	○	○	■	■	○	1
Passive Treatment Walls	Pilot	Δ	Solid	No	■	■	○	■	■	□	Δ	□	3
Slurry Walls (containment only)	Full	■	NA	NA	○	○	○	○	○	■	■	■	3
Vacuum Vapor Extraction	Pilot	Δ	Liquid Vapor	No	■	○	■	□	Δ	■	○	○	3
Bioreactors	Full	■	Solid	No	■	■	■	Δ	○	○	NA	■	3
Air Stripping	Full	■	Liquid Vapor	No	■	○	○	Δ	Δ	■	NA	■	2
Filtration	Full	■	Solid	Yes	Δ	Δ	Δ	■	○	■	■	■	1
Ion Exchange	Full	■	Solid	Yes	Δ	Δ	Δ	■	Δ	■	○	■	1
Liquid-phase Carbon Absorption	Full	■	Solid	No	■	■	○	○	■	■	NA	Δ	2
Precipitation	Full	■	Solid	Yes	Δ	Δ	Δ	■	□	■	○	■	1
UV Oxidation	Full	■	None	No	■	■	■	Δ	■	Δ	NA	○	4
Natural Attenuation	NA	■	None	No	■	■	■	Δ	Δ	■	Δ	■	1

Notes:

A	=	Development Status	H	=	Inorganics	M	=	Cost Driver	■	=	Better
B	=	Availability	I	=	Explosives	1	=	Neither	○	=	Average
C	=	Residuals Produced	J	=	System Reliability/	2	=	Operations &	Δ	=	Worse
D	=	Treatment Train	J	=	Maintainability			Maintenance	□	=	Inadequate Data
E	=	Volatile Organic Compounds	K	=	Cleanup Time	3	=	Capital	NA	=	Not Applicable
F	=	Semivolatile Organic Compounds	L	=	Overall Cost	4	=	Both	NPDES	=	National Pollutant DischargeElimination System
UV	=	Ultraviolet	POTW	=	Public Owned Treatment Works	5	=	Inadequate Data			
G	=	Fuels									

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Table B-1
Additional Treatment Technologies Screening Matrix

Technology	A	B	C	D	E	F	G	H	I	J	K	L	M
Groundwater, Surface Water, and Leachate (cont'd)													
No Action	Full	■	All	No	○	○	○	○	○	Δ	Δ	Δ	1
pH Adjustment	Full	■	Solid	No	Δ	○	Δ	■	○	■	■	■	1
Reverse Osmosis	Full	○	Liquid Solid	No	Δ	Δ	■	■	■	■	○	Δ	4
Wet Air Oxidation	Full	○	Solid	No	■	■	○	○	○	○	■	○	4
UV Reduction	Full	○	None	Yes	■	■	○	○	○	○	○	○	1
Sedimentation	Full	■	Liquid Solid	No	Δ	Δ	Δ	■	Δ	■	○	■	2
Oil/Water Separation	Full	■	Liquid Solid	No	■	■	■	Δ	Δ	■	■	■	2
Dissolved Air Flotation	Full	■	Liquid Solid	No	■	■	■	Δ	Δ	■	■	○	4
Resin Adsorption	Full	○	Liquid Solid	No	○	○	Δ	○	○	○	○	○	4
Land Application	Full	○	Liquid Solid	No	○	○	○	■	Δ	○	Δ	○	2
Aquatic Plant Systems	Full	Δ	Liquid Solid	No	Δ	○	Δ	■	■	○	Δ	■	2
Natural Wetlands	Full	■	None	Yes	○	■	Δ	■	■	Δ	Δ	■	2
Air Emissions/Offgas Treatment													
Biofiltration	Full	○	None	NA	■	○	■	Δ	○	Δ	NA	○	1
High-energy Corona	Pilot	Δ	None	NA	■	■	■	○	Δ	Δ	NA	○	5
Membrane Separation	Pilot	Δ	None	NA	■	○	○	Δ	○	Δ	NA	○	5

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Table B-1
Additional Treatment Technologies Screening Matrix

Technology	A	B	C	D	E	F	G	H	I	J	K	L	M
Air Emissions/Offgas Treatment (cont'd)													
Oxidation	Full	■	None	NA	■	■	■	Δ	○	■	NA	■	1
Vapor-phase Carbon Absorption	Full	■	Solid	NA	■	■	■	○	■	■	NA	■	1
No Action	Full	■	All	No	○	○	○	○	○	Δ	Δ	Δ	1
Flare	Full	■	None	Yes	■	○	○	Δ	Δ	■	■	■	3
Condensers	Full	■	Liquid	No	■	■	■	Δ	○	○	○	○	4
Absorbers	Full	■	Liquid	Yes	■	○	○	Δ	○	○	○	○	4
Filter Fabric	Full	■	Solid	No	Δ	Δ	Δ	○	Δ	○	○	○	4
Electrostatic Precipitators	Full	○	Solid	No	Δ	Δ	Δ	■	Δ	■	○	○	3
Wet Scrubbers	Full	○	Liquid Solid	Yes	○	Δ	Δ	■	Δ	○	○	○	4
Dust Suppressants	Full	■	None	Yes	Δ	○	Δ	■	Δ	■	Δ	■	2
Removal, Containment, and Disposal Options													
Groundwater Extraction	Full	■	Liquid	No	■	■	■	■	■	■	○	■	2
Leachate Collection	Full	■	Liquid	No	■	■	■	■	■	○	○	○	2
POTW	Full	■	Liquid	No	■	■	■	■	■	■	■	■	2
NPDES Discharge	Full	■	Liquid	No	■	■	■	■	■	○	○	■	2
Reinjection	Full	■	Liquid	No	■	■	■	■	■	○	○	○	2
Surface Controls	Full	■	Solid	No	Δ	○	Δ	○	○	○	Δ	○	2
Capping	Full	■	Solid	No	Δ	○	Δ	○	○	■	Δ	Δ	2
Landfill	Full	■	Solid	No	Δ	○	Δ	■	○	■	Δ	Δ	4

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Table B-1
Additional Treatment Technologies Screening Matrix

Technology	A	B	C	D	E	F	G	H	I	J	K	L	M
Removal, Containment, and Disposal Options (cont'd)													
Storm Water Controls	Full	■	Liquid Solid	No	Δ	○	Δ	■	○	■	Δ	Δ	2
Dredging	Full	■	Liquid Solid	No	Δ	○	○	■	○	■	■	Δ	2
Clean, Inspect, and Repair Sewer Lines	Full	■	Liquid Solid	No	Δ	○	○	○	Δ	○	○	○	2
Long-term Monitoring	Full	■	All	No	Δ	Δ	Δ	Δ	Δ	○	Δ	■	2
Institutional Controls	Full	■	All	No	Δ	Δ	Δ	Δ	Δ	○	Δ	■	2
Intrinsic	Full	■	All	No	Δ	Δ	Δ	Δ	Δ	Δ	Δ	■	2

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Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
SOIL, SEDIMENT, AND SLUDGE	
In Situ Biological Treatment	
Biodegradation	The activity of naturally occurring microbes is stimulated by circulating water-based solutions through contaminated soil to enhance in situ biological degradation of organic contaminants. Nutrients, oxygen, or other amendments may be used to enhance biodegradation and contaminant desorption from subsurface materials.
Bioventing	Oxygen is delivered to contaminated unsaturated soil by forced air movement (either extraction or injection of air) to increase oxygen concentrations and stimulate biodegradation.
White Rot Fungus	White rot fungus has been reported to degrade a wide variety of organopollutants by using their lignin-degrading or wood-rotting enzyme system. Two different treatment configurations have been tested for white rot fungus, in situ and bioreactor.
In Situ Physical/Chemical Treatment	
Pneumatic Fracturing	Pressurized air is injected beneath the surface to develop cracks in low-permeability and over-consolidated sediments, opening new passageways (i.e., effective permeability) that increase the effectiveness of many in situ processes and enhance extraction efficiencies.
Soil Flushing	Water, or water containing an additive to enhance contaminant solubility, is applied to the soil or injected into the groundwater to raise the water table into the contaminated soil zone. Contaminants are leached into the groundwater, which is then extracted and treated.
Soil Vapor Extraction	Vacuum is applied through extraction wells to create a pressure/concentration gradient that induces gas-phase volatiles to diffuse through soil to extraction wells. The process includes a system for handling offgasses. This technology also is known as in situ soil venting, in situ volatilization, enhanced volatilization, or soil vacuum extraction.
Solidification/ Stabilization	Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization).

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
In Situ Thermal Treatment	
Thermally Enhanced Soil Vapor Extraction	Steam/hot air injection or electric/radio frequency heating is used to increase volatilization and mobility of vapor phase contaminants to facilitate extraction. The process includes a system of handling offgases.
Vitrification	Electrodes for applying electricity are used to melt contaminated soil and sludge, producing a glass and crystalline structure with very low leaching characteristics.
Ex Situ Biological Treatment (assuming excavation)	
Composting	Contaminated soil is excavated and mixed with bulking agents and organic amendments such as wood chips, animal and vegetative wastes, which enhance the porosity and organic content of the mixture to be decomposed.
Controlled Soil-phase Biological Treatment	Excavated soil are mixed with soil amendments and placed in above ground enclosures. Processes include prepared treatment beds, biotreatment cells, soil piles, and composting.
Landfarming	Contaminated soil is applied onto the soil surface and periodically turned over or tilled into the soil to aerate the waste.
Slurry-Phase Biological Treatment	An aqueous slurry is created by combining soil or sludge with water and other additives. The slurry is mixed to keep solids suspended and microorganisms in contact with the soil contaminants. Upon completion of the process, the slurry is dewatered and the treated soil is disposed of.
Ex Situ Physical/Chemical Treatment (assuming excavation)	
Chemical Reduction/ Oxidation	Reduction/oxidation chemically converts hazardous contaminants to nonhazardous or less-toxic compounds that are more stable, less mobile, and/or inert. The oxidizing agents most commonly used are ozone, hydrogen peroxide, hypochlorites, chlorine, and chlorine dioxide.
Base Catalyzed Decomposition Dehalogenation	Contaminated soil is screened, processed with a crusher and pug mill, and mixed with NaOH and catalysts. The mixture is heated in a rotary reactor to dehalogenate and partially volatilize the contaminants.
Glycolate Dehalogenation	An alkaline polyethylene glycol (APEG) reagent is used to dehalogenate the halogenated aromatic compounds in a batch reactor. Potassium polyethylene glycol (KPEG) is the most common APEG reagent. Contaminated soil and the reagent are mixed and heated in a treatment vessel. In the APEG process, the reaction causes the polyethylene glycol to replace halogen molecules and render the compound nonhazardous. For example, the reaction between chlorinated organics and KPEG replaces a chlorine molecule and reduces toxicity.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
Ex Situu Physical/Chemical Treatment (assuming excavation) (cont'd)	
Soil Washing	Contaminants sorbed onto fine soil particles are separated from bulk soil in an aqueous-based system based on particle size. The wash water may be augmented with a basic leaching agent, surfactant, pH adjustment, or chelating agent to help remove organics and heavy metals.
Soil Vapor Extraction	A vacuum is applied to a network of aboveground perforated piping passing through the excavated material to facilitate volatilization of organics from the excavated media. The process includes a system for handling offgases.
Solidification/ Stabilization	Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization).
Solvent Extraction	Waste and solvent are mixed in an extractor, dissolving the organic contaminant into the solvent. The extracted organics and solvent are then placed in a separator, where the contaminants and solvent are separated for treatment and future use.
Ex Situ Thermal Treatment (assuming excavation)	
High-Temperature Thermal Desorption	Wastes are heated to 315-538°C (600-1,000°F) to volatilize water and organic contaminants. A carrier gas or vacuum system transports volatilized water and organics to the gas treatment system.
Hot Gas Decontamination	The process raises the temperature of the contaminated equipment or material for a specified period of time. The gas effluent from the material is treated in an afterburner system to destroy all volatilized contaminants.
Incineration	High temperatures, 87-1,204°C (1,600-2,200°F), are used to combust (in the presence of oxygen) organic constituents in hazardous wastes.
Low-Temperature Thermal Desorption	Wastes are heated to 93-315°C (200-600°F) to volatilize water or organic contaminants. A carrier gas or vacuum system transports volatilized water and organics to the gas treatment system.
Open Burn/Open Detonation (OB/OD)	In OB operations, explosives or munitions are destroyed by self-sustained combustion, which is ignited by an external source, such as flame, heat, or a detonatable wave (that does not result in a detonation). In OD operations, detonatable explosives and munitions are destroyed by a detonation, which is initiated by detonating a disposal charge.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
Ex Situu Thermal Treatment (assuming excavation) (cont'd)	
Pyrolysis	Chemical decomposition is included in organic materials by heat in the absence of oxygen. Organic materials are transformed into gaseous components and a solid residue (coke) containing fixed carbon and ash.
Vitrification	Contaminated soil and sludge are melted at high temperature to form a glass and crystalline structure with very low leaching characteristics.
Other Treatment	
Excavation and Offsite Disposal	Contaminated material is removed and transported to permitted offsite treatment and disposal facilities. Pretreatment may be required.
Natural Attenuation	Natural subsurface processes - dilution, volatilization, biodegradation, absorption, and chemical reactions with subsurface materials — are allowed to reduce contaminant concentrations to acceptable levels.
No Action	No action is taken.
Filter Press	Contaminated soil, sediment, and sludge are dewatered by slinging, squeezing, or sucking. The objective is to reduce moisture content and increase solids content.
GROUNDWATER, SURFACE WATER, AND LEACHATE	
In Situ Biological Treatment	
Cometabolic Processes	This emerging application involves the injection of water containing dissolved methane and oxygen into groundwater to enhance methanotrophic biological degradation.
Nitrate Enhancement	Nitrate is circulated throughout groundwater contamination zones as an alternative electron acceptor for biological oxidation of organic contaminants by microbes.
Oxygen Enhancement with Air Sparging	Air is injected under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of organic contaminants by naturally occurring microbes.
Oxygen Enhancement with Hydrogen Peroxide	A dilute solution of hydrogen peroxide is circulated throughout a contaminated groundwater zone to increase the oxygen content of groundwater and enhance the rate of aerobic biodegradation of organic contaminants by microbes.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
In Situ Physical/Chemical Treatment	
Air Sparging	Air is injected into saturated matrices to remove contaminants through volatilization. Vaporization components rise to the unsaturated zone, where they are removed by vacuum extraction and then treated.
Directional Wells (enhancement)	Drilling techniques are used to position wells horizontally, or at an angle, in order to reach contaminants not accessible via direct vertical drilling.
Dual-phase Extraction	A high-vacuum system is applied to simultaneously remove liquid and gas from low-permeability or heterogeneous formations.
Free-product Recovery	Undissolved liquid-phase organics are removed from subsurface formations, either by active methods (e.g., pumping) or a passive collection system.
Hot Water or Steam Flushing/Stripping	Steam is forced into an aquifer through injection wells to vaporize volatile and semivolatile contaminants. Vaporization components rise to the unsaturated zone where they are removed by vacuum extraction and then treated.
Hydrofracturing (enhancement)	Pressurized water is injected through wells to crack low-permeability, over consolidated sediments. Cracks are filled with porous media that serve as avenues for bioremediation or to improve effective hydraulic conductivity.
Passive Treatment Walls	These barriers allow the passage of water while prohibiting the movement of contaminants by employing such agents as chelators (liquids selected for their specificity for a given metal), sorbents, microbes, and others.
Slurry Walls	These subsurface barriers consist of vertically excavated trenches filled with slurry. The slurry, usually a mixture of bentonite and water, hydraulically shores the trench to prevent collapse and retard groundwater flow.
Vacuum Vapor Extraction	Air is injected into a well, lifting contaminated groundwater in the well and promoting additional groundwater flow to the well. Once inside the well, some of the volatile organics in the contaminated groundwater are transferred from the water to air bubbles, which rise and are collected at the top of the well by vapor extraction.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
Ex Situu Biological Treatment (assuming pumping)	
Bioreactors	Contaminants in extracted groundwater are put into contact with microorganisms in attached or suspended growth biological reactors. In suspended systems, such as activated sludge, contaminated groundwater is circulated in an aeration basin. In attached systems, such as rotating biological contactors and trickling filters, microorganisms are established on an inert support matrix.
Ex Situ Physical/Chemical (assuming pumping)	
Air Stripping	Volatile organics are partitioned from groundwater by increasing the surface area of the contaminated water exposed to air. Aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration.
Filtration	Filtration isolates solid particles by running a fluid stream through a porous medium. The driving force is either gravity or a pressure differential across the filtration medium.
Ion Exchange	Ion exchange removes ions from the aqueous phase by exchange with innocuous ions on the exchange medium.
Liquid-phase Carbon Adsorption	Groundwater is pumped through a series of canisters or columns containing activated carbon to which dissolved organic contaminants adsorb. Periodic replacement or regeneration of saturated carbon is required.
Precipitation	This process transforms dissolved contaminants into an insoluble solid, facilitating the contaminant's subsequent removal from the liquid phase by sedimentation or filtration. The process usually uses pH adjustment, addition of chemical precipitant, and flocculation.
UV Oxidation	Ultraviolet (UV) radiation, ozone, and/or hydrogen peroxide are used to destroy organic contaminants as water flows to the treatment cell. An ozone destruction unit may be needed to treat offgases from the treatment tank.
Other Treatment	
Natural Attenuation	Natural subsurface processes – such as dilution, volatilization, biodegradation, absorption, and chemical reactions with subsurface materials – are allowed to reduce contaminant concentrations to acceptable levels.
No Action	No action is taken.
pH Adjustment	Acids or bases are added to change the hydrogen ion concentration of a mixture.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
Other Treatment	
Reverse Osmosis	Removes organic compounds from water mixtures using membrane processes. Process will remove organics with a molecular weight greater than 200.
Wet Air Oxidation	Destroys organic compounds in aqueous solutions by inducing oxidation and hydrolytic reactions at high temperature and pressure.
UV Reduction	Chemically reduces organics in water mixtures through simultaneous application of UV light and a proprietary liquid or adsorbent solid catalyst.
Sedimentation	The physical separation of particles from water mixtures by gravity.
Oil/Water Separation	The physical separation of aqueous-phase liquids from water mixtures by gravity or density differences.
Dissolved Air Flotation	Compressed air is released into a waste water which is then released to the atmosphere causing particles and oils to separate from a water mixture and float where they can be recovered.
Resin Adsorption	Contaminants are transferred from the dissolved state to the surface of the resin. The resin can be regenerated by removing the contaminants with steam or solvent.
Land Application	Dilute solution of contaminants is applied to the land surface by spraying or flooding. Inorganic contaminants will attenuate to the soil by cation exchange or precipitation. Organic contaminants may biodegrade.
Aquatic Plant Systems	Water plants are grown in diluted contaminated waters. Once plants get to mature size, they can be harvested and properly disposed of. Aquatic plants may uptake contaminants and either use them as energy or attenuate them.
Natural Wetlands	Either natural wetlands or man-made wetlands are ecological systems of native plants, insects, and animals which thrive in low marshy areas. Contaminants are either attenuated or used as energy by the plants and soil in these systems.
Oxidation/Reduction	The process involve with the transfer of electrons from one species to another.
AIR EMISSIONS/OFFGAS TREATMENT	
Biofiltration	Vapor-phase organic contaminants are pumped through a soil bed and sorb to the soil surface, where they are degraded by microorganisms in the soil.
High-energy Corona	This processes uses high-voltage electricity to destroy volatiles at room temperature.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
AIR EMISSIONS/OFFGAS TREATMENT (cont'd)	
Membrane Separation	This organic vapor/air separation technology involves the preferential transport of organic vapors through a nonporous gas separation membrane (a diffusion process analogous to putting hot oil on a piece of waxed paper).
Oxidation	Organic contaminants are destroyed in a high temperature 1,000°C (1,832°F) combustor.
Vapor-phase Carbon Adsorption	Offgases are pumped through a series of canisters or columns containing activated carbon to which organic contaminants adsorb. Periodic replacement or regeneration of saturated carbon is required.
Flares	Landfill gases are pumped through a flame, where they are ignited.
Condensers	Gases and vapors are pumped through a chamber where they come into contact with plates or coils which are cooler, thus condensing the gases or vapors.
Adsorbers	Resins are used to separate contaminants from air or vapor streams. This technology is similar to vapor-phase carbon adsorption.
Filter Fabrics	Fabric filters are used to trap contaminant-laden particles from air streams. Fabrics come in different mesh sizes.
Electrostatic Precipitators	Electric current or charge is used to trap particles of opposite charge. This is more effective with particles of relative small sizes.
Wet Scrubber	Water or solvent droplets capture contaminants and particles from air streams. The water or solvent contaminated solution can then be treated.
Dust Suppressants	Fluids including water are applied to soil, sediment, or sludge surfaces to prevent fine particles from becoming airborne.
Removal, Containment, Disposal Options	
Groundwater Extraction	Pumps are used to remove groundwater. This process dewaters an aquifer or removes water at a specific yield.
Leachate Collection	A system of trenches, pipes, or other conveyances which are used to intercept a groundwater and/or surface water and contaminants mixture resulting from a particular site.
POTW	A public owned treatment works (POTWs), like North Charleston sewage treatment facility, treats domestic and industrial waste.

Table B-2
Definition of Matrix Treatment Technologies

Technology	Description
Removal, Containment, Disposal Options (cont'd)	
NPDES Discharge	A National Pollutant Discharge Elimination System (NPDES) permit is used to control the discharge of pollutants to waters of the states and United States.
Land Application	Wastewaters applied to surface soil for the purpose of evaporation or infiltration. Land application is considered to be a nondischarge under NPDES permitting.
Reinjection	The aquifer is recharged by pumping or leaching wastewaters back into the aquifer using wells or subsurface drains.
Surface Controls	These measures are designed to reduce or prevent direct contact with contaminated surface soil and to reduce the spread of contaminants by volatilization, tracking, tidal action, or wind.
Capping	Capping is an engineering control in which an area of contamination is covered to reduce surface infiltration and direct contact with the contaminants.
Landfill	A landfill is an engineering control where contaminants are placed in or on the ground and covered. A landfill may have liners on the bottom, sides, and top. A landfill may be used to contain contaminants or encapsulate them.
Storm Water Controls	These are best management practices to control the release of storm water and to control and reduces erosion and sedimentation.
Dredging	This is the process of using hydraulic pumps or draglines to remove soil, sediment, and sludge from water bodies.
Clean, Inspect, and Repair Sewer Lines	Storm, sanitary, and industrial sewer lines convey contaminants and water mixtures to treatment facilities or disposal points. Contaminants may be trapped and accumulate in the lines or lines may become damaged causing them to either exfiltrate or infiltrate contaminants. Lines can be cleaned using a number of methods including but not limited to pressure washing, pigging, brushing, etc. Inspection can be made by visual or sounding. Repairs can be accomplished by slip lining, grouting, or replacement.
Long-term Monitoring	This is the process of sampling and analyzing impacted environmental media over a period of years.
Institutional Controls	These are controls like deed restrictions, posting signs, erecting fences and other barriers which may restrict use or access to a contaminated area.
Intrinsic	This is the process of using natural attenuation to contain contaminants with other technologies to enhance attenuative process, such as precipitation, ion exchange, bioremediation, reduction, oxidation, dilution, etc.